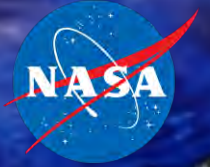


National Aeronautics and  
Space Administration



# EXPLORE EARTH

## **ESTO Perspective on Technology for STV**

STV Information Systems Technology Breakout

September 15, 2020

**Bob Bauer**

**NASA** Earth Science Technology Office

ESTO Deputy Program Manager/DSI Program Manager

# Earth Science Technology Program Elements

ESTO manages, on average, 120 active technology development projects. Over 830 projects have completed since 1998.

## Advanced Technology Initiatives Program (ATIP)

### Advanced Component Technologies (ACT)

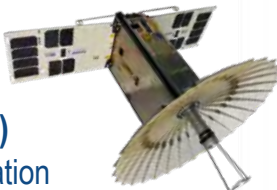
Critical components and subsystems for advanced instruments and observing systems



12 projects awarded in 2018  
**Solicitations in FY20 and FY22**  
Average award: \$1.2M (2-3 years)  
Average selection rate: 16.4%

### In-Space Validation of Earth Science Technologies (InVEST)

On-orbit technology validation and risk reduction for small instruments and instrument systems.



Four projects selected in FY18  
**Solicitations planned in FY21 and FY24**  
Average award: \$3-5M (3 years)  
Average selection rate: 18.3%

## Instrument Incubator Program (IIP)

Earth remote sensing instrument development from concept through breadboard and demonstration

**19 projects awarded in Oct 2019**  
*Solicitations planned in FY21 and FY23*  
Average award: \$4.5M (3 years)  
Average selection rate: 23.2%



## Advanced Information Systems Technology (AIST)

Innovative on-orbit and ground capabilities for communication, processing, and management of remotely sensed data and the efficient generation of data products

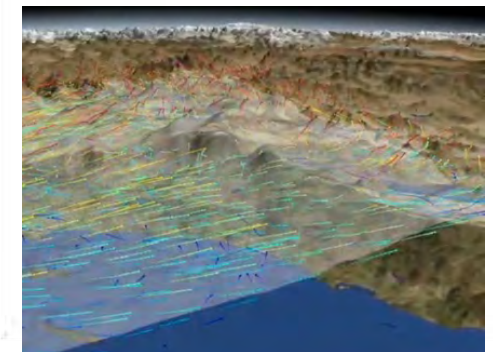
**22 projects awarded in Sept 2019**  
*Solicitations planned in FY21 and FY23*  
Average award: \$1.2M (2 years)  
Average selection rate: 19.6%

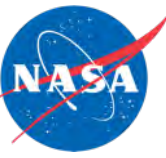


## Decadal Survey Incubation (DSI)

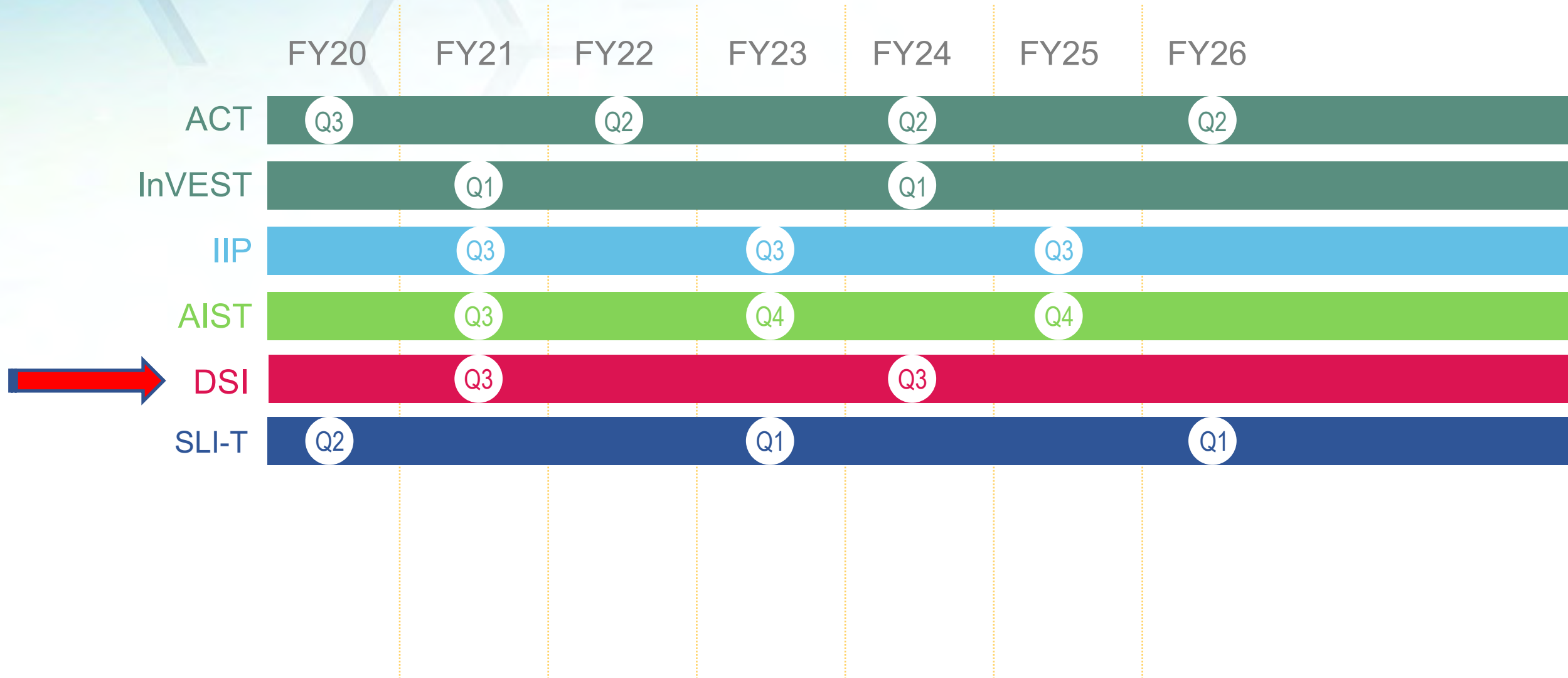
Maturation of observing systems, instrument technology, and measurement concepts for Planetary Boundary Layer and Surface Topography and Vegetation observables through technology development, modeling/system design, analysis activities, and small-scale pilot demonstrations

**2 Study teams awarded in FY20**  
*Solicitation planned in FY21*

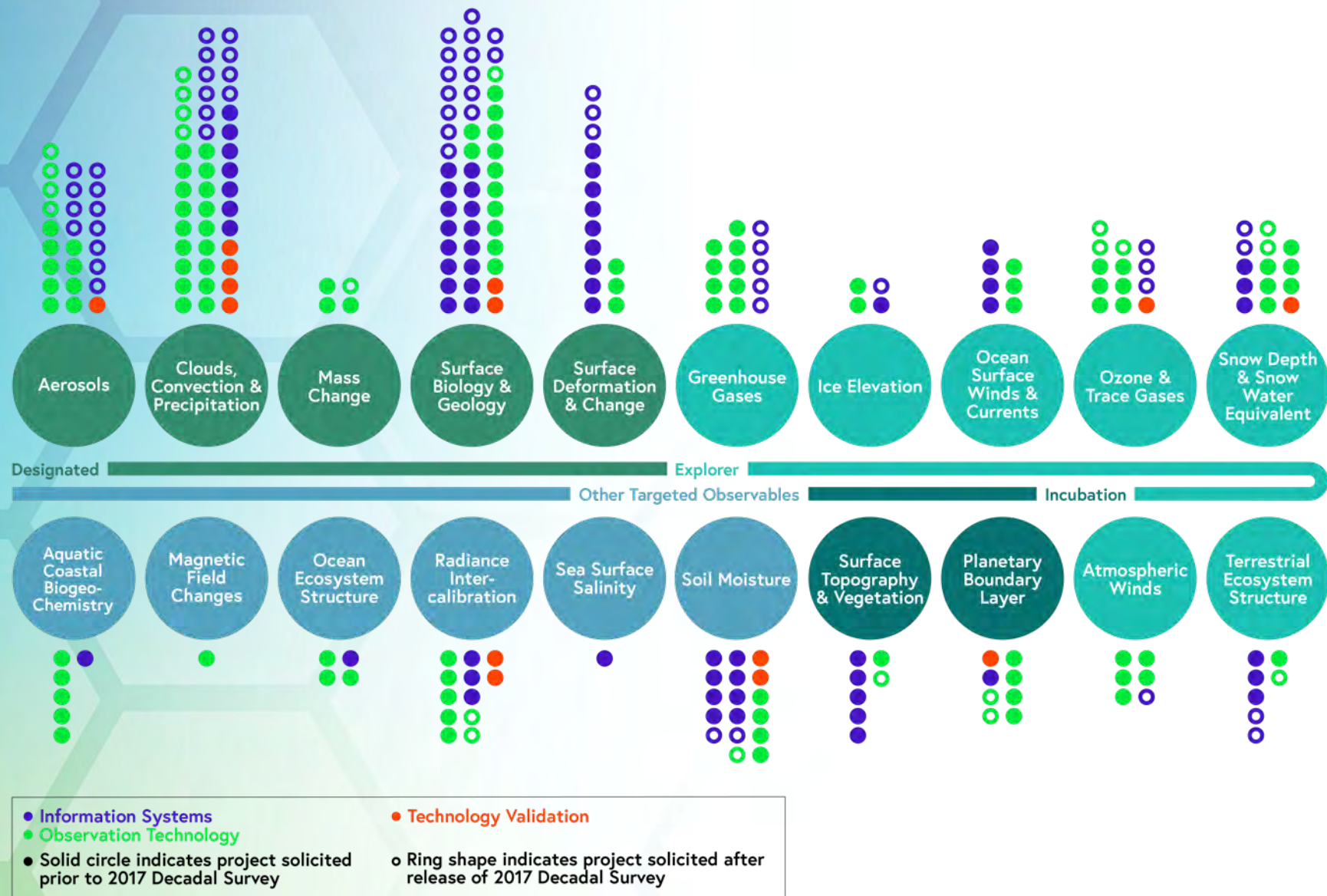




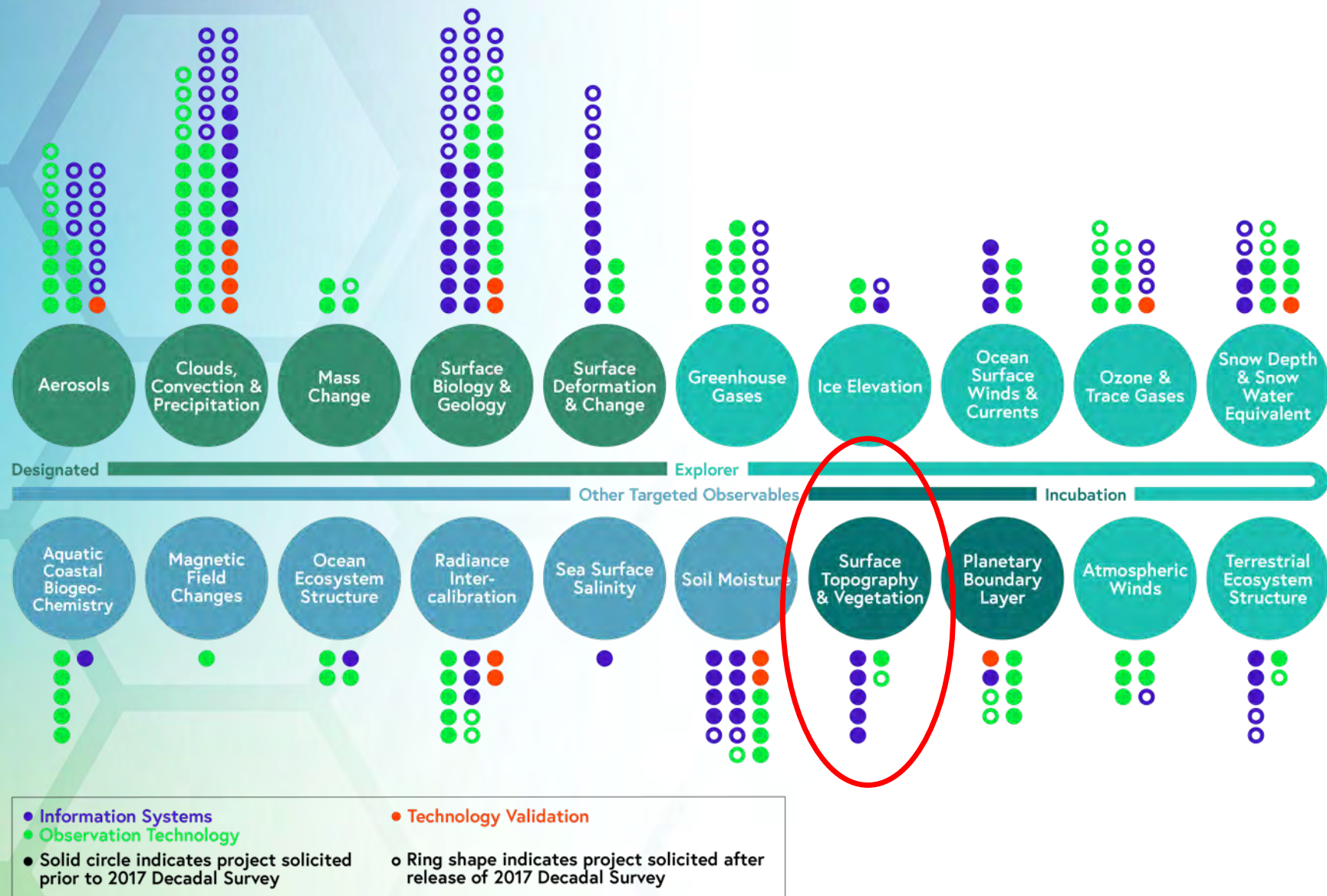
# ESTO Upcoming Solicitations



# ESTO Projects Supporting the 2017 Decadal Survey



# ESTO Projects Supporting the 2017 Decadal Survey



# Recently Completed STV Relevant Tasks in ESTO Portfolio

## COMPLETED

- Ranson (GSFC): Miniaturized Imaging Spectrometer to Measure Vegetation Structure and Function – MiniSpec IIP-16-0049 (completed 2020)
- Wye (SRI): CubeSat Imaging Radar for Earth Science: Instrument Development and Demonstration (CIRES-IDD) IIP-16-0066 (completed 2020)
- Nemani (ARC): Framework for Mining and Analysis of Petabyte-size Time-series on the NASA Earth Exchange (NEX) AIST-16-0137 (completed 2020)
- French (USC ISI): SpaceCube X: On-board processing for Distributed Measurement and Multi-Satellite Missions AIST-16-0031 (completed 2020)
- Neigh (GSFC): Automated Protocols for Generating Very High-Resolution Commercial Validation Products with NASA HEC Resources AIST-16-0105 (completed 2020)

# Recently Current STV Relevant Tasks in ESTO Portfolio

## ONGOING

- Lavalle (JPL): Distributed Aperture Radar Tomographic Sensors (DARTS) to Map Three-Dimensional Vegetation Structure and Surface Topography IIP-19-0028
- Yang (GSFC): Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System (CASALS) IIP-19-0052
- Yueh (JPL): Signals of Opportunity Synthetic Aperture Radar for High Resolution Remote Sensing of Land Surfaces IIP-19-0034
- Sun (GSFC): Characterizing Selex HgCdTe APDs for Space Lidar Applications ATI-QRS-17-0001
- Donnellan (JPL): Quantifying Uncertainty and Kinematics of Earthquake Systems (QUAKES-A) Analytic Center Framework AIST-18-0001

# Decadal Survey Incubation Overview/Plans

- A new program element in the 2017 Decadal Survey, focused on investments for priority observation capabilities needing advancement prior to cost-effective implementation
- Two elements: Planetary Boundary Layer (PBL), and Surface Topography and Vegetation (STV)
- Supports maturation of mission, instrument, technology, and/or measurement concepts to address specific high priority science (for 2027-2037 decade)
- Assigned to ESTO to manage, however, is run as a partnership between ESTO and R&A
- Funding profile (\$M):

	<u>FY20</u>	<u>FY21</u>	<u>FY22</u>	<u>FY23</u>	<u>FY24</u>	<u>FY25</u>
Original FY 22	8.0	0.0	20.0	20.0	15.0	15.0
<b>Proposed PPBE22</b>	8.0	<b>3.0</b>	<b>17.0</b>	20.0	15.0	15.0

- PLANS**
- FY21 – complete Study Teams; continuation of augmented tasks (CS labor); release DSI ROSES-21 solicitation
  - FY22 – Begin funding new ROSES awards; some directed work possible
  - ROSES-21 DSI Solicitation (targeting release in late Spring)
    - Will use Study Team white papers to inform NASA in writing the call
    - Anticipate awards up to ~\$1.5M/y for 3 years (although still TBD att)
    - # of awards TBD, as is split between STV and PBL

# Surface Topography and Vegetation

## Team Overview

Ben Phillips, HQ Program Scientist; Bob Connerton, ESTO Technology Lead

### Study Team

Andrea Donnellan, Study Team Science Lead

Dave Harding, Study Team Technology Co-Lead

Alex Gardner

Cathleen Jones

Yunling Lou

Paul Lundgren

Sassan Saatchi

Marc Simard

Jason Stoker

Robert Treuhaft

Konrad Wessels



# STV Augmentation Updates

- **G-LiHT Upgrade, PI: Bruce Cook (GSFC) - \$250k**
  - Initiated procurement to purchase a Phase One multispectral, survey-grade stereo aerial camera for integration and test with G-LiHT airborne imaging system
  - Compared terrain elevation, vegetation height and structure using G-LiHT lidar, G-LiHT optical and UAV optical data for a shrub biomass paper, submitted
  - Finishing papers describing the physical-based methods used to create 3D reconstructions from G-LiHT data
- **Advanced Optical DEMS, PI: Jim Tucker (GSFC) - \$195k**
  - Significant progress on EarthDEM stereo processing of coastlines, faults, and volcanoes, usually with multiple passes
  - Initial products are nearly ready for distribution to NASA or US Government-funded solid Earth investigators
  - Working with NSF, NGA, and NASA Data Systems Program to secure free and open release
- **ICESat-2-GEDI Fusion, PI: Scott Luthcke (GSFC) - \$250k**
  - Significant progress on mathematical algorithm and software framework for bald Earth fusion products
  - Initial modification to Science Data Processing System for GEDI data support complete
  - Initial database of ICESat-2 and GEDI relevant Level-1 and -2 data products constructed and tested
  - Initial algorithm and software framework for vegetation canopy height gridding has been developed and tested
- **UAVSAR Imager, PI: Andrea Donnellan (JPL) - \$200k**
  - Progress optimizing cameras and flight sensor software for Quantifying Uncertainty and Kinematics of Earth Systems Imager (QUAKES-I)
  - Completed QUAKES-I SRR (April 9) and QUAKES-I Payload PDR (May 7)
- **Lidar Bathymetry (FINESST), PI: Jeffrey Thayer (U of Colorado) - \$45k/yr**
  - Awaiting yr2 report and yr3 proposal via FINESST program

## FY21 Augmentations Plans

- All 1yr projects proposed for continuation for a second year
- Collecting SOW and budgets, nominally at yr1 funding levels
- Funds (\$1M) for NASA/ESA French Guyana joint airborne campaign re-phased to FY21

# Technology Gaps – RB perspective

- LIDAR
  - Spacebased Lidar with sufficient output power, especially at smaller size, weight, cost, reliability
  - Achievable to get to a smallsat size?
- Radar
  - Lightweight deployable apertures
  - Component miniaturization to enable smallsat solutions
  - Power efficiency / Thermal dissipation
  - Multibands in “single” system (e.g., L-, X-, Ku-, Ka)
  - Cross-spacecraft calibration in a constellation (e.g. CubeSat solution)
- Stereo Photogrammetry
  - Satellite derived bathymetry
  - Integration of SP with Lidar
- Information Systems
  - Improving on-board processing of large data volumes
  - Integration of cross-platform data sets (e.g., space, airborne, in situ)
  - Integration of data processing into sensor systems
  - Sensor system autonomy for use on UAS/HALE/HAPS



# BACK-UP

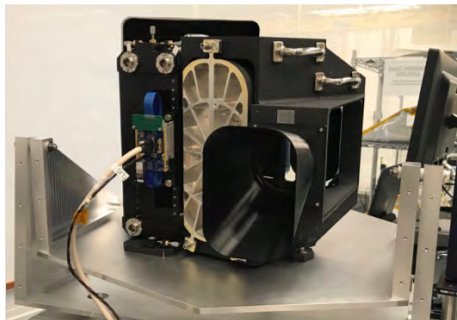
# Other ESD Technology Activities Managed by ESTO

ESTO also manages focused technology development and integration projects on behalf of the Earth Science Division's (ESD) Research and Flight programs

## Sustainable Land Imaging – Technology (SLI-T)

- Funds provided by the Flight Program
- **SLI-T** develops innovative technologies to achieve future land imaging (Landsat) measurements with more efficient instruments, sensors, components and methodologies.

*6 projects awarded in August 2020*  
*Average award: \$3.2M (2-5 years)*  
*Average selection rate: 26.7%*



## Earth Venture Instruments – Technology (EVI-T)

- Funds provided by the Flight Program's Earth Systems Science Pathfinder (ESSP) program
- **EVI-T** develops promising, highly-rated Earth Venture Instrument proposals that require additional technology risk reduction

*Average award: \$3-7M*



## Airborne Instrument Technology Transition (AITT)

- Funds provided by the R&A program
- **AITT** provides campaign ready airborne instrumentation to support the objectives of the R&A Program. AITT converts mature instruments into operational suborbital assets that can participate in field experiments, evaluate new satellite instrument concepts, and/or provide cal/val for satellite instruments.

*4 projects selected in March 2020*  
*Average award: \$1.2M (2 years)*



## Ocean Biology and Biogeochemistry

- Funds provided by the R&A Program
- **Ocean Color Remote Sensing Vicarious Calibration Instruments** program develops in situ vicarious calibration instrument systems to maintain global climate-quality ocean color remote sensing of radiances and reflectances

*Average award: \$2.3M*



# 10-Year ESTO Infusions Snapshot (2008-2019)

In just the past 10 years, ESTO principal investigators have reported at least 122 infusions of their technologies into Earth science missions, science campaigns, and other operational or commercial activities. What follows is the breakout of infusions since 2008, with lists of major missions and campaigns.

## Earth Science Flight Mission Infusions: 36

**NASA:** AIRS, ASCENDS (pre-formulation work), CATS-ISS, CLARREO-PF, CSIM-FD, DESDyni/NISAR, EO-1, GEOCAPE, GPM, GRACE-2, GRACE-FO, MISR, MODIS, NISAR, **PACE**, SMAP, SWOT; **Other Government Agencies:** COSMIC-2, COSMO-SkyMed, MicroMAS, NOAA/EUMETSAT Sentinel-6

## Other (non-ESD) Flight Mission Infusions: 13

**NASA:** ARM, CubeSat Hydrometric Atmospheric Radiometer Mission-CHARM, NASA DSN / NSF Green Bank Telescope, Interplanetary NanoSat Pathfinder In Relevant Environment (INSPIRE) mission, ISS Raven, Restore-L, RRM3, SDO; **Other Government Agencies:** AFRL Mid-Star, Air Force Enterprise Ground System

## Earth Venture Infusions: 37 (20 out of 26, or 77%, of Earth Venture selections include ESTO heritage)

**EV-Suborbital:** ABOVE, ACT-America, ACTIVATE, AirMOSS, ATTREX, CARVE, Delta-X, DISCOVER-AQ, HS3, IMPACTS, NAAMES, OMG, ORACLES, S-MODE; **EV-Instrument:** ECOSTRESS, GEDI, MAIA, TEMPO, TROPICS; **EV-Mission:** GeoCarb; **EV-I Technology:** TEMPEST-D

## Airborne Campaign Infusions: 21

**NASA:** Cloud Radar System, CORAL, Deep Convective Cloud & Chemistry (DC3) Field Campaign, GCPEX, GRIP, IceBridge, IceSat Gap Filler, MB08, Mid Latitude Continental Convective Clouds Experiment (MC3E), MIZOPEX, Polar Winds, SMAPVEX08, UAVSAR; **Other Government Agencies:** NSF-ORCAS, State of California-Great Southern CA Shakeout, DoE-TCAP, Virginia Coastal Energy Research Consortium - Offshore Wind Turbine Study; **Industry:** Chevron – Airborne Methane Campaign

## Data Centers/Data Access: 11

**NASA:** Giovanni, NASA Unified Weather Research & Forecasting (NU-WRF), NCCS DASS, **PO.DAAC**, TCIS, TOPS-NEX; **Other Government Agencies:** CEOS/GEOSS, Various In-situ Sensor Webs, NOAA ESRL, NSF Semantic eScience Framework, USGS Hawaiian Volcano Observatory; **Other:** Various In-situ Sensor Webs

## Commercial Application: 2

Boeing Next-gen ComSat, Navy Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV)

## AO Proposal Infusions: 2

ATHENA-OAWL, Discovery-Lunar Volatiles Orbiter

*most recent infusions*

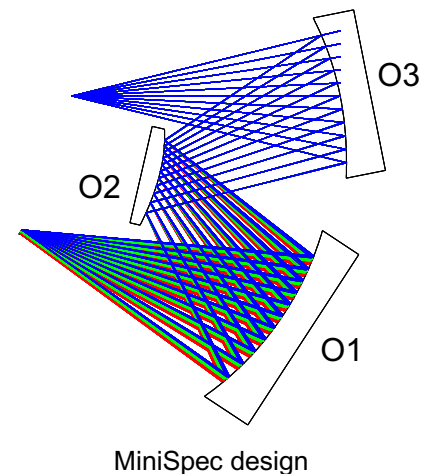


# A Diurnal Constellation of Miniaturized Imaging Spectrometers for Vegetation Structure and Function - MiniSpec

PI: K. Jon Ranson, NASA GSFC

## Objective

- Develop and test MiniSpec - an instrument concept to reduce size and mass of a hyperspectral spectrometer to acquire reflected solar radiation in the visible to shortwave of the electromagnetic spectrum (VSWIR; 450nm–1650nm) to monitor vegetation health, carbon, water, and energy exchanges.
  - Include in the instrument concept the requirement to produce instruments for diurnal sampling of spatial and spectral measurements using a modular instrument design and constellation of small satellites.
- Demonstrate that the instrument concept can be augmented by an advanced focal plane architecture and super-resolution processing techniques to produce < 2m resolution measurements of 3D vegetation structure.



O-3 mirror



O-2 mirror with etched grating



O-1 mirror

Delivered O1-O3 freeform optics during initial characterization

## Accomplishments

- Worked with science community to develop science traceability matrix to address science questions relevant to vegetation structure and function types.
- Designed and built MiniSpec, a freeform optics spectrometer including design and procurement of freeform optics O1, O3 mirrors, and O2 mirror with etched grating from aluminum (shown above) with surface figure of  $0.083\lambda$  RMS (tolerance  $<0.2\lambda$ ).
- Characterized MiniSpec optics and conducted initial bread board tests using newly developed contactless techniques and data analysis approaches for measuring optics with “freeform” prescriptions.
- Developed miniaturized panchromatic instrument (Mini3D) to acquire high-resolution panchromatic images suitable for producing three-dimensional digital surface models of vegetation canopies.
  - Mini3D design is being used as part of diurnal SmallSat constellation concept.
- Developed super resolution software approach to combine multiple offset images to enhance nascent resolution of Mini3D from 3 m to 1 m.

**Co-Is/Partners:** J. Howard, P. Dabney, J. LeMoigne, P. Thompson, R. Ohl, K. Thome, GSFC; F. Huemmerich, UMBC; G. Sun, UMCP/ESSIC; W. Czaja, UMCP; M. Mareboyana, Bowie State U.

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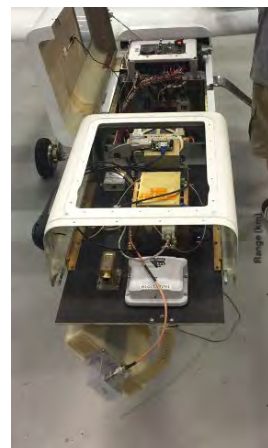


# CubeSat Imaging Radar for Earth Science: Instrument Development and Demonstration (CIRES-IDD)

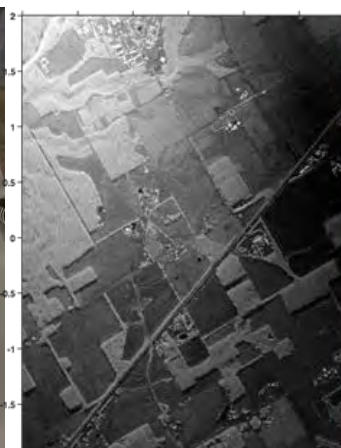
PI: Lauren Wye, SRI International

## Objective

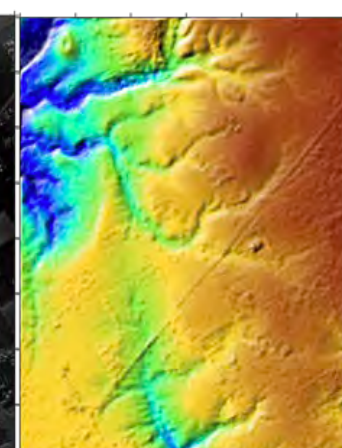
- Develop a full S-band (2.9-3.5 GHz) radar instrument capable of interferometric synthetic aperture radar (InSAR) operations for a CubeSat platform.
  - Build high-gain deployable antenna (>36 dBi) and test in relevant environments.
  - Integrate existing InSAR radar imaging software.
  - Refine the thermal and power management solution.
- Demonstrate the instrument capabilities using a low-cost unmanned aerial system (UAS) from NASA ARC
  - 25 m SAR imaging resolution, sub-cm level InSAR accuracy, SNR >13 dB performance.



CIRES SIERRA-B  
UAV Payload



CIRES 5 m resolution  
SAR Image



Digital elevation map derived  
from CIRES InSAR data

## Accomplishments

- Developed Tx/Rx module, high speed processing module (>500 GFLOPs), and high-powered amplifier (600 W peak (60 W avg)) for S-band radar. Integrated and flight tested the CIRES instrument on manned and unmanned aircrafts.
- Tested the CIRES instrument on Cessna 206 over Kilauea summit for 6 hours to demonstrate forming of SAR images
- Upgraded CIRES instrument's bandwidth to 200 MHz to achieve 5 m spatial resolution.
- Developed the fairing for NASA Sierra-B to accommodate the instrument for flight testing. Flew the instrument at 2,400 ft to demonstrate forming of SAR images and height measurements.
- Validated CIRES InSAR performance with mm-level deformation accuracy in a controlled urban flooding experiment at Army Muscatatuck Urban Training Center (MUTC) in Indiana.
- Designed 1.6 m x 3.2 m high-gain deployable membrane antenna (>36 dBi) for 16U CubeSat. Built a subarray (1/4 size) antenna and performed functional tests including RF performance and repeat deployment.
- Developed CIRES instrument 16U CubeSat preliminary design to support InSAR operation from 500 km altitudes.

**Co-Is/Partners:** P. Rennich, S. Lee, M. Huff, E. Frenklak, R. Sparr, S. Gulkin, M. Schutzer, L. Tao, B. Nation, SRI; P. Warren, S. Torrez, C. Kory, PSI; S. Yun, JPL; S. Cahill, A. Mazzulla, M. Fladeland, NASA ARC

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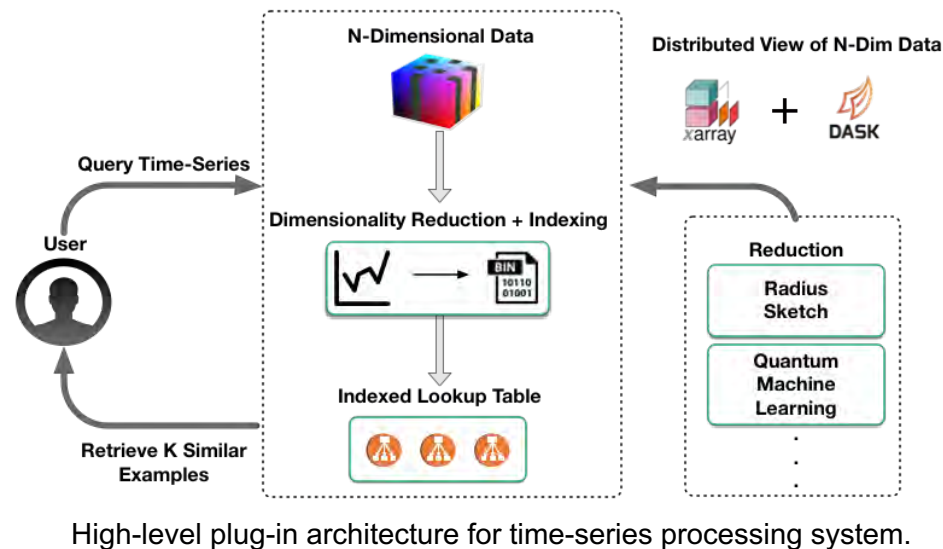
# Framework for Mining and Analysis of Petabyte Sized Time-series on the NASA Earth Exchange

PI: Rama Nemani, ARC

## Objective

Create a capability for fast and efficient mining of time-series data from NASA's satellite-based observations, model output, and other derived datasets.

- Facilitate analyzing long-term records by removing the burden on researchers of large-scale physical data transformations and processing, metadata handling and cataloging, and general data and storage management.
- Provide quantum-assisted capabilities for:
  - time-series analysis.
  - machine learning.
  - data compression.

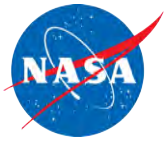


## Accomplishments

- Developed a data query engine and an indexer for time-series data using Radius Sketch, Xarray and Dask.
- Developed a quantum-assisted variational autoencoder for multivariate high-dimensional search problems with low memory requirements and efficient querying.
- Prototyped user interface with OceanWorks-based community mapping client and integrated with other components (e.g., query engine) on the NASA Advanced Supercomputing (NAS) infrastructure.

**Co-Is/Partners:** E. Rieffel, M. Wilson, T. Vandal, A. Michaelis, J. Becker, ARC

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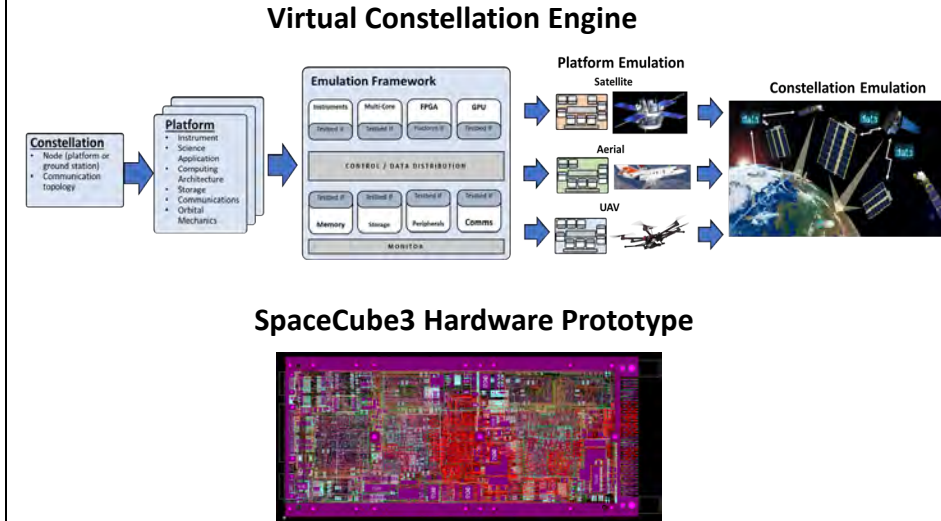
# SpaceCubeX2: On-board Processing for Distributed Measurement and Multi-Satellite Missions

PI: Matthew French, USC/ISI

## Objective

To develop on-board processors capable of supporting emerging Earth science measurement requirements of 10—100x processing performance to enable:

- **Distributed sensing** which exchanges or fuses UAV and satellite measurements.
- **Multi-satellite constellations** which provide diurnal or multi-angle measurements.
- **Intelligent sensor** control to increase the scientific value of data collected and instrument longevity.



## Accomplishments

- Developed Virtual Constellation Engine end-to-end simulation and modeling of heterogenous constellations and distributed systems in the cloud.
  - Developed a cloud-computing-based virtual machine environment to enable emulation scaling to constellation-level modeling including instrument, on-board compute, science application, and communications.
- SpaceCube3 is on path to achieve greater than 14x processing improvement over previous generation space hardware.
- Multispectral Imaging, Detection and Active Reflectance (MiDAR) application achieved 13,500 fps, a 45x increase over initial processing goal.
- Developed and released the Hot & sPyC software, which enables software developers to utilize Python and to map to hardware accelerator cores.

**Co-Is/Partners:** Alessandro Geist, NASA GSFC; Ved Chirayath, NASA ARC

TRL<sub>in</sub> = 3    TRL<sub>out</sub> = 4



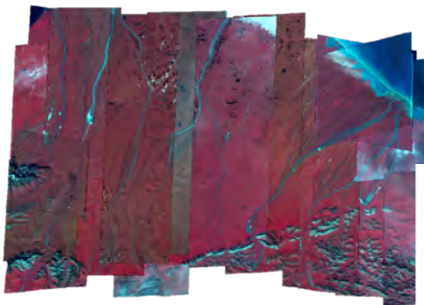
# Automated Protocols for Generating Very High-Resolution Commercial Validation Products with NASA HEC Resources

PI: Chris Neigh, NASA GSFC

## Objective

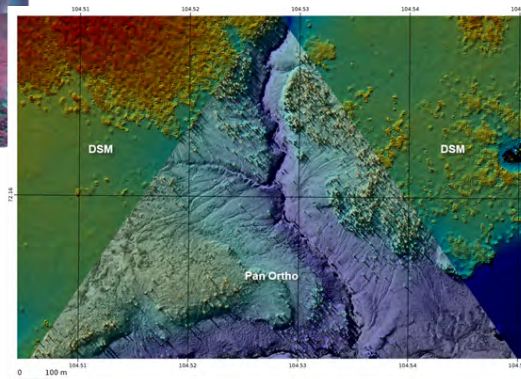
Enhance scientific utility of sub-meter DigitalGlobe (DG) data towards revolutionizing processing of very high-resolution (VHR) data into science-ready datasets by automating intermediate steps by:

- Improving VHR data discovery using databases and mosaic datasets within NASA GSFC's ADAPT global archive of DG VHR imagery.
- Producing on demand VHR 1/2° mosaics; automating estimates of surface reflectance, ortho-rectifying and normalized 1 m mosaics for pan and 2m for multi-spectral.
- Producing on-demand 2m posting digital elevation models (DEMs) leveraging high-end computing (HEC) processing and open source Ames Stereo Pipeline software.



WorldView (WV) Stereo and color-shade relief DEM with a panchromatic pseudo color orthorectified image in northern Siberia (center). Image Credit: DigitalGlobe Nextview 2012

On-demand regional mosaic of 29 strips. An example of an orthorectified and co-registered multi-temporal, spatially continuous image.



## Accomplishments

- Developed an API to process on-demand DigitalGlobe very high-resolution data to ortho-rectified top of atmosphere (TOA) reflectance and DEMs with NASA's ADAPT HEC.
  - Enables the discovery of VHR data through a user interface that is able to produce image previews and filter by sensor, location, or season.
  - Enables the production of on-demand ortho-rectified and co-registered multi-temporal, panchromatic 0.3 - 0.5 m and unsharpened 2-m multispectral imagery for a spatially continuous and temporally consistent reference.
- Demonstrated the potential cost savings and science value of very high-resolution data with specific application to biodiversity (forest structure, vegetation composition), cryosphere (ice elevation, snow depth), hydrology (water level) and others.

**Co-Is/Partners:** M. Carroll, NASA GSFC; P. Montesano, NASA GSFC/SSAI; D. Slayback, NASA GSFC/SSAI; A. Lyapustin, NASA GSFC; D. Shean, UW; O. Alexandrov, NASA ARC/SGT

TRL<sub>in</sub> = 2    TRL<sub>out</sub> = 4



# Distributed Aperture Radar Tomographic Sensors (DARTS) to Map Three-Dimensional Vegetation Structure and Surface Topography

PI: Marco Lavallo, JPL

## Objective

Mature and demonstrate SAR tomographic measurement technologies that will enable formations of satellites to acquire measurements of global vegetation structure and surface topography when coupled with recent developments in miniaturized spaceborne radars. These technologies include:

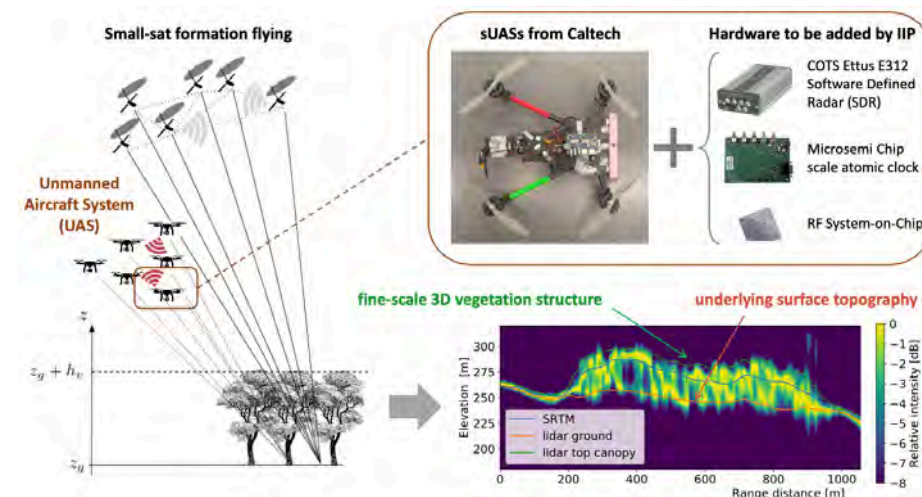
- Mutual synchronization between DARTS members;
- Relative position knowledge of DARTS members with cm-level accuracy ( $\sim\lambda/20$ );
- Multi-static SAR processing from raw data to tomograms;
- Observational geometry configuration optimization;
- Integrated system performance environment; and
- SmallSat compatible, light-weight deployable antennas.

## Approach

- Develop and assess synchronization and relative localization algorithms via field/bench tests.
- Generate radar tomograms from synchronized signals acquired by small unmanned aircraft systems (sUASs) for changing geometry/site.
- Conduct integrated trade-study analysis with orbital, scene, radar, and platform parameters via simulations informed by synchronization/localization algorithm assessment.
- Build and test light-weight, deployable, antenna with mechanical support for Transmit/Receive and Receive-only SmallSats.

**Co-Is/Partners:** B. Hawkins, R. Beauchamp, M. Haynes, R. Ahmed, N. Chahat, P. Focardi, I. Seker, D. Hawkins, S. Prager, JPL; Soon-Jo Chung, M. Anderson, Caltech

DARTS concepts: satellite formation, hardware, and TomoSAR profile



## Key Milestones

- |   |       |
|---|-------|
| • Implement compact L-band radars   | 10/20 |
| • Integrate distributed radars + sUASs  | 02/21 |
| • Collect multi-static radar observations with post-processing synchronization              | 06/21 |
| • Collect multi-static radar observations with real-time synchronization                    | 11/21 |
| • Report results on system trade study, science traceability, system design and performance | 01/22 |
| • Complete initial processing for DARTS measurements  | 05/22 |
| • Generate multi-static and tomographic data products                                       | 02/23 |
| • Report on antenna design, measured performance, and path-to-flight                        | 02/23 |

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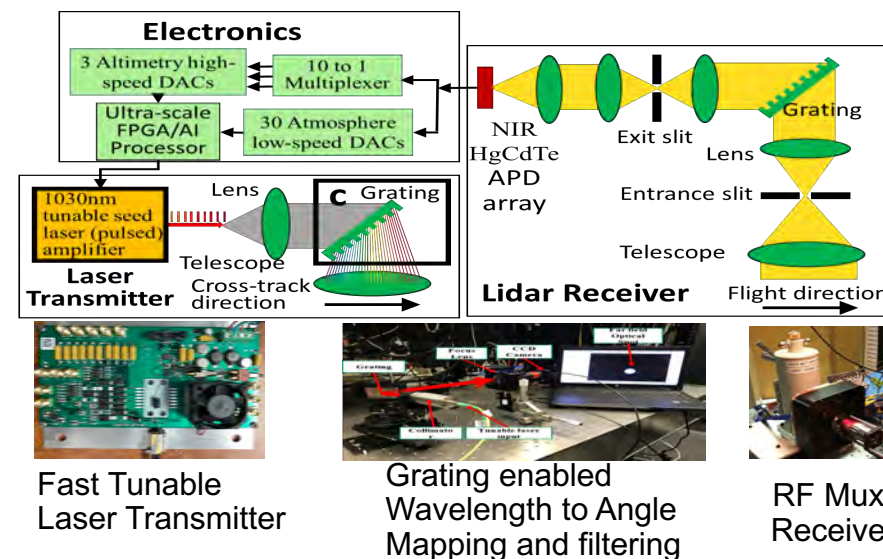


# Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System (CASALS): Instrument Development and Demonstration

PI: Guangning Yang, NASA GSFC

## Objective

- Develop an architecture for a SmallSat observing system that integrates an adaptive lidar, concurrent hyperspectral imaging and on-board AI technologies to measure structural and functional properties for topography, vegetation, snow, ice sheets and the surface-atmosphere boundary layer.
- Develop a highly-efficient 1030 nm lidar system that uses three key emerging technologies: a photonic integrated circuit (PIC) seed laser, a high peak-power fiber amplifier, and a linear mode photon-sensitive detector array.
  - The laser transmitter can rapidly steer a single high-power laser beam across 1200 resolvable footprints (separated by 6m, the FWHM of the footprint), dynamically reconfiguring the distribution of the laser footprints across a 7.2km wide area.



## Approach

- Complete science and measurement requirements formulation based on the integration of advanced lidar and spectrometer system.
- Develop PIC fast tunable laser at 1030 nm and time synchronized pulse modulation for multi-wavelength pulse train.
- Develop and integrate end to end seed laser electronics with path to space electronics.
- Develop the lidar receiver using high quantum efficiency detector array and a novel, grating-based approach for wide-band, passive rejection of solar background noise.
- Perform CASALS lidar integration and performance validation through ground-based demonstration.

**Co-Is/Partners:** Dave Harding, Jeff Chen, Mark Stephen, GSFC; Freedom Photonics; Univ. of California, Santa Barbara

## Key Milestones

• Requirements, architecture and design	06/20
• Control electronics design and fabrication	12/20
• Wavelength to angle mapping assembly	11/21
• PIC fast tunable laser development	12/21
• Receiver multi-wavelength filter assembly	12/21
• Receiver RF 10-to-1 Multiplexer assembly	02/22
• Tunable seed laser transmitter integration and testing	05/22
• National Instrument based Lidar electronics	08/22
• Lidar, testing and characterization	03/23

TRL<sub>in</sub> = 2      TRL<sub>current</sub> = 2

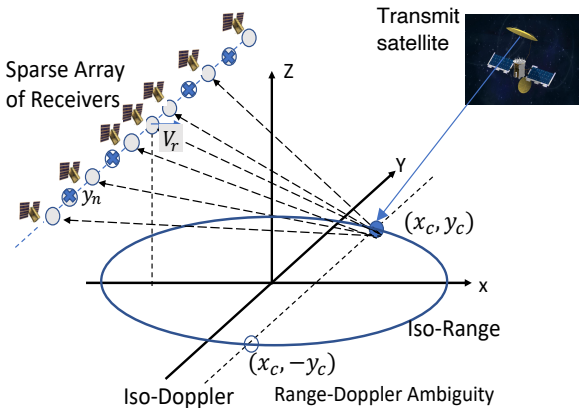


# Signals of Opportunity Synthetic Aperture Radar for High Resolution Remote Sensing of Soil moisture and Snow

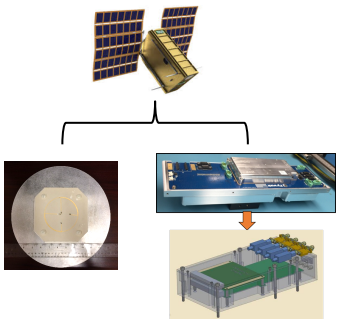
PI: Simon Yueh, JPL

## Objective

- Develop SAR technology based on a unique combination of P-band Signals of Opportunity (SoOp) technique and sparse array technology for high resolution satellite remote sensing of Snow Water Equivalent and Root Zone Soil Moisture to achieve:
  - Proof-of-concept demonstration of the SoOpSAR technology by ground-based experiments, and
  - Advancement of the SoOpSAR system concept through trade studies for resolution, swath, sparse array optimization, and uncertainty analysis of receiver timing and positioning errors.
- SoOpSAR measurements are needed for modeling of land surface hydrological processes and applications. These also provide the needed information on terrestrial snow water storage – one of the Earth Explorer measurement objectives in the 2017 Decadal Survey report.



Formation flying of small SoOp receivers with SAR processing for ~100m spatial resolution.



Compact SoOpSAR instrument consisting of a planar antenna and a Blackjack-based receiver for smallsat.

## Approach

- Perform SoOpSAR system performance analysis.
- Develop several SAR receivers for testing.
- Mount the receivers with various horizontal spacings on a ground-based moving vehicle to acquire data to simulate and test the sparse array concept for high across-track resolution processing.
- Conduct detailed system error analyses to determine the requirements on sparse array position control and knowledge accuracy requirements for spaceborne operations.

**Co-Is/Partners:** Rashmi Shah, Xiaolan Xu, Bryan Stiles, Javier Bosch-Lluis, Garth Franklin, JPL; Chi-Chih Chen, OSU

## Key Milestones

- |                                       |       |
|---------------------------------------|-------|
| • System requirements                 | 06/20 |
| • Preliminary subsystem build         | 10/20 |
| • Receiver and antenna build          | 02/21 |
| • SoOpSAR system integration and test | 05/21 |
| • Proof-of-concept experiment         | 07/21 |
| • Data analysis and report            | 10/21 |

TRL<sub>in</sub> = 2      TRL<sub>current</sub> = 2



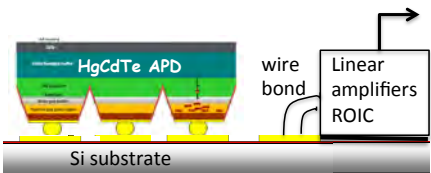
# Characterizing Selex HgCdTe APDs for Space Lidar Applications

PI: Xiaoli Sun, NASA/GSFC

## Objective

Evaluate the HgCdTe avalanche photodiode (APD) arrays from Selex/Leonardo for higher speed lidar receiver applications:

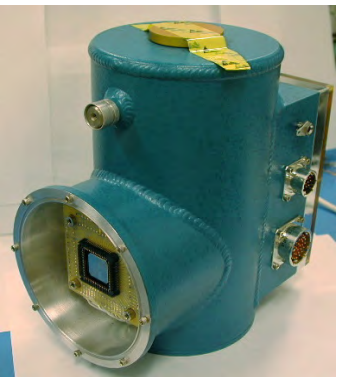
- Specify the detector chip and preamplifier for the procurement.
- Characterize the resulting devices and publish the results.
- Compare the device performance with the existing HgCdTe APD arrays by DRS/Leonardo used in the previously developed CO<sub>2</sub> and CH<sub>4</sub> lidar.



Typical APD detector cross section.



Packaged APD detector with preamplifier in an LCC pack.



Packaged APD detector LCC pack in a LN2 dewar for electro-optical tests.

## Approach

- Work with Selex to specify HgCdTe APD detector hybrid with integrated high-speed pre-amplifier circuit useful for lidar receivers.
- Procure the detector system from Selex.
- Characterize the detector system in the GSFC lidar detector laboratories.
- Compare the Selex HgCdTe APD performance to the existing DRS HgCdTe APDs.

## Key Milestones

- |                                       |       |
|---------------------------------------|-------|
| • Develop detector specifications     | 03/17 |
| • Place order for detectors           | 05/17 |
| • Assemble test setup                 | 12/17 |
| • Detector delivery from Selex        | 10/18 |
| • Detector characterization           | 04/19 |
| • Reporting the results at conference | 11/19 |

**Co-Is/Partners:** Keith Barnes, Selex/Leonardo, UK

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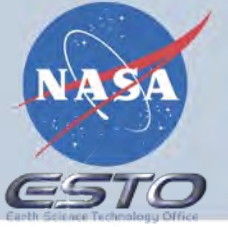


# *New Observing Strategies (NOS) for Future Earth Science Concepts*

Jacqueline Le Moigne  
NASA ESTO  
*AIST Program*

September 15, 2020

# AIST Thrusts: NOS and ACF



- New Observing Strategies (NOS)

*Optimize measurement acquisition using many diverse observing capabilities, collaborating across multiple dimensions and creating a unified architecture*

- Using Distributed Spacecraft Missions (DSM) or SensorWebs at various vantage points
- In response to Decadal Survey mission design needs, forecast or science model-driven, or event-driven
- Using NASA- as well as non-NASA data sources or relevant services
- AIST18: Developing required capabilities and technologies

- Analytic Center Frameworks (ACF)

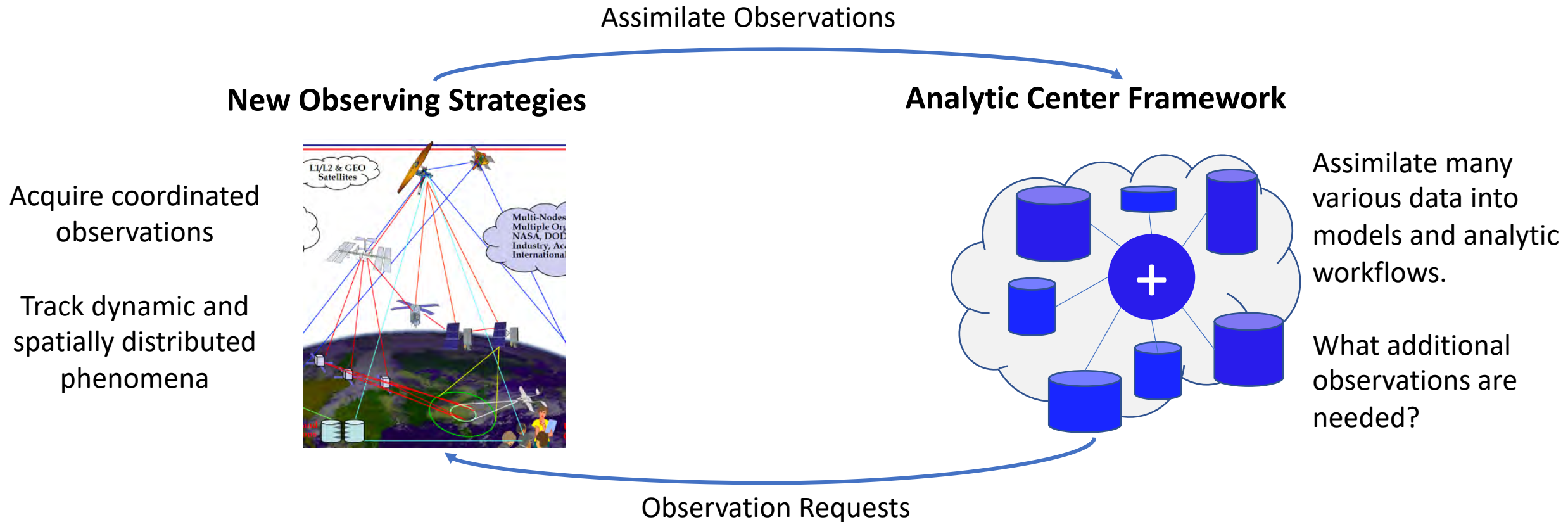
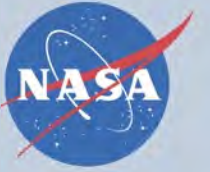
*Enhance and enable focused Science investigations by facilitating access, integration and understanding of disparate datasets using pioneering visualization and analytics tools as well as relevant computing environments*

- Allowing flexibility/tailoring configurations for Science investigators to choose among a large variety of datasets & tools
- Reducing repetitive work in data access and pre-processing, e.g., developing reusable components
- AIST18: Assessing general frameworks and computational environments for selected Designated Observables

- More generally, address general "Science Data Intelligence":

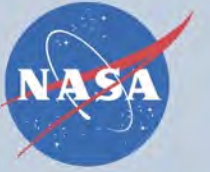
- "Starting with Science, Ending with Science"
- Extracting knowledge and information from Science data to make "Science decisions"

# NOS and ACF for Science Data Intelligence

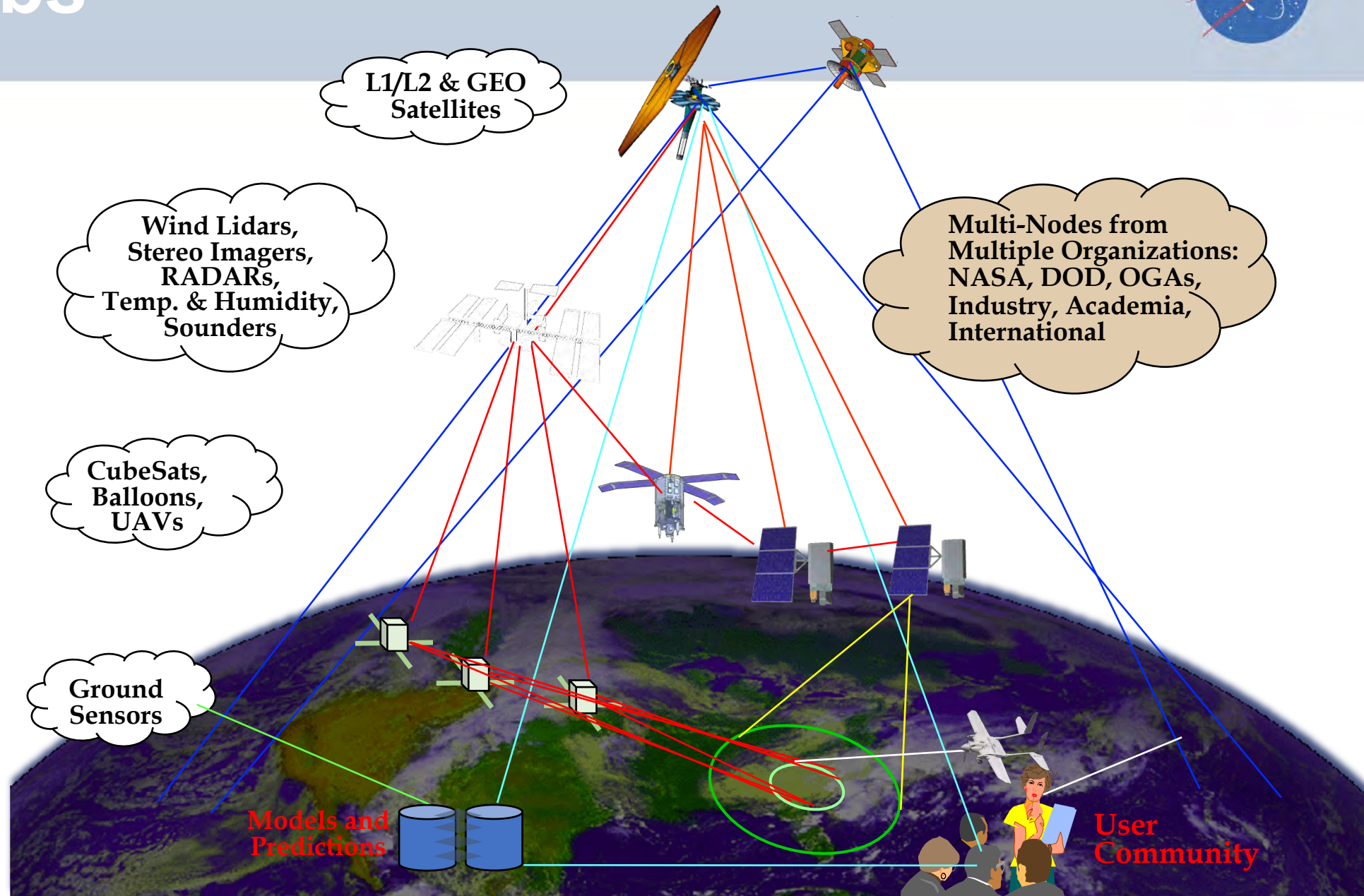


**NOS+ACF acquires and integrates complementary and coincident data to build a more complete and in-depth picture of science phenomena**

# SensorWebs



A **SensorWeb** is a distributed system of **sensing nodes** (space, air or ground) that are interconnected by a **communications fabric** and that functions as a single, highly coordinated, virtual instrument. It semi- or -autonomously detects and dynamically reacts to events, measurements, and other information from constituent sensing nodes and from external nodes by modifying its observing state so as to *optimize mission information return*. (e.g., EO-1 SensorWeb 3G). (Ref: Talabac et al, 2003)



# Distributed Spacecraft Missions (DSM)

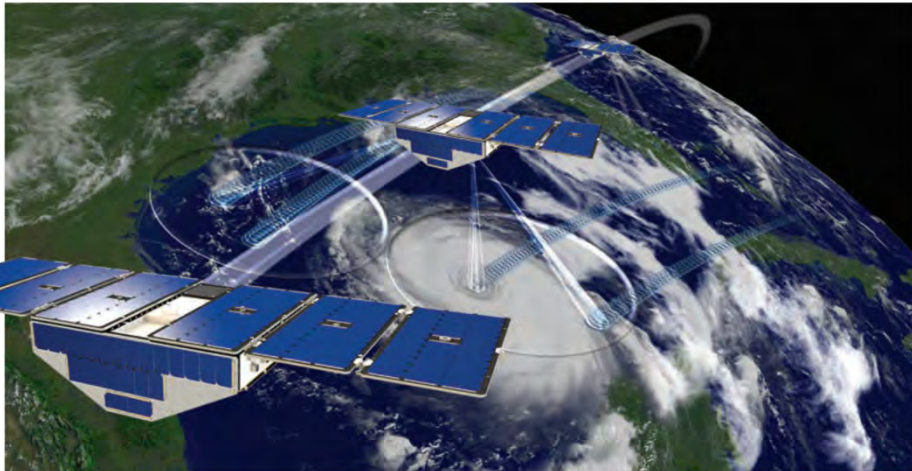


## Distributed Spacecraft Missions (DSM):

A Distributed Spacecraft Mission (DSM) is a mission that involves multiple spacecraft to achieve one or more common goals.

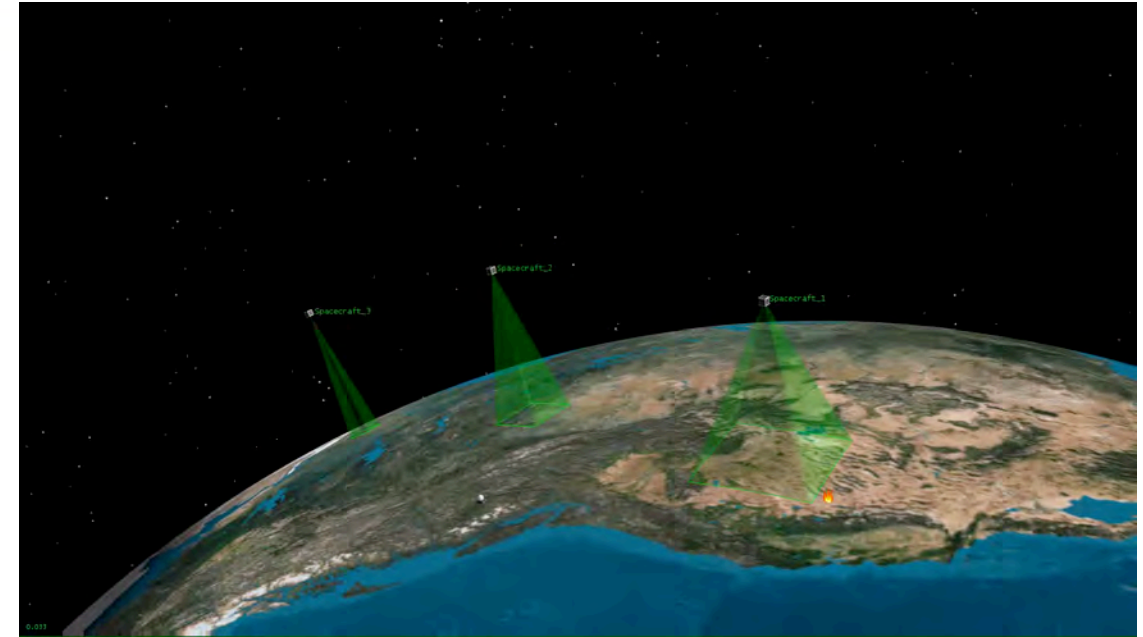
Can provide:

- **Multi-perspective observation (angular, spatial, spectral, temporal)**, for fundamental physical understanding of dynamic phenomena
- **Multi-point measurements** for full observation coverage



Using a constellation of eight small satellites enables frequent observations

CYGNSS microsatellite observatories in orbit. Image credit: Southwest Research Institute



A special case of DSM is an **Intelligent and Collaborative Constellation (ICC)** which involves the combination of:

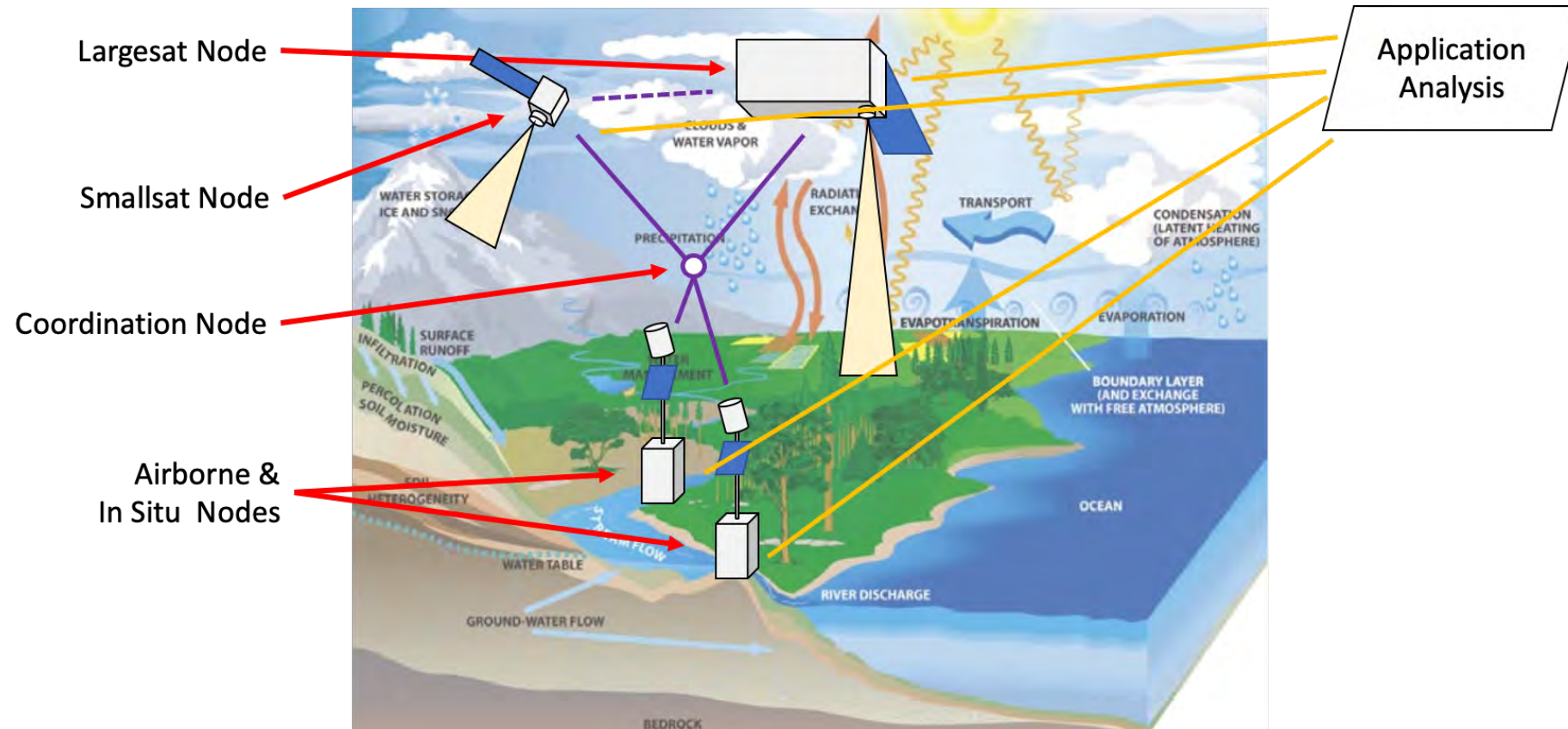
- Real-time data understanding
- Situational awareness
- Problem solving;
- Planning and learning from experience
- Communications and cooperation between multiple S/C

# New Observing Strategies (NOS)

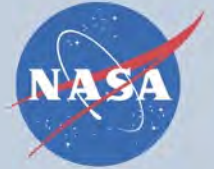
## New Observing Strategies (NOS):

- Multiple collaborative sensor nodes producing measurements integrated from multiple vantage points and in multiple dimensions (spatial, spectral, temporal, radiometric)
- Provide a dynamic and more complete picture of physical processes or natural phenomena

NOS = Intelligent, Collaborative and Generalized SensorWeb Concept in which each Node can be Individual Sensor or DSM

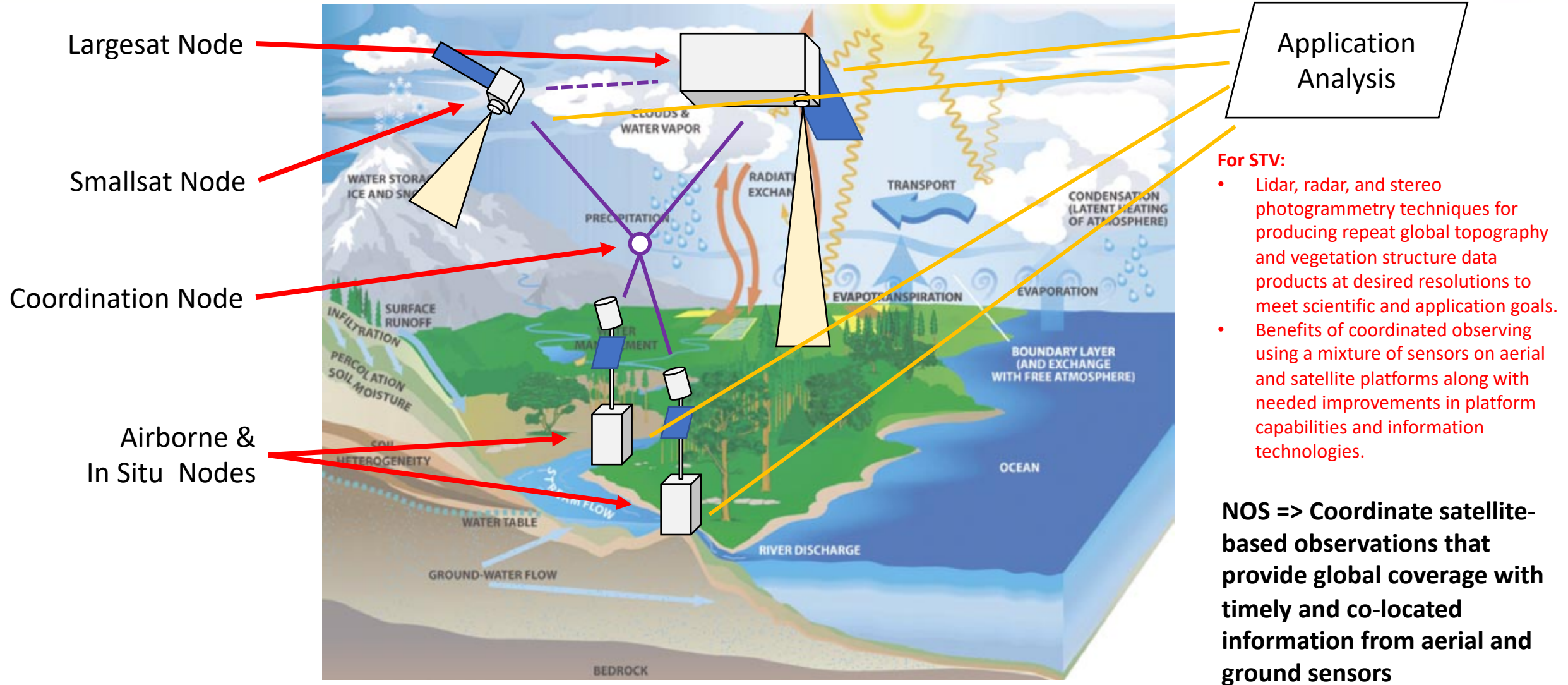


# NOS Application Cases



<b>Mission Type</b> <i>Timeframe</i> <i>Application</i>	<b>Tactical Observing System</b> <i>Seconds-minutes</i> <i>Point event/phenomenon</i>	<b>Operational Observing System</b> <i>Hours-days</i> <i>Spatial phenomenon</i>	<b>Strategic Observing System</b> <i>Months-years</i> <i>Spatial-temporal phenomenon</i>
<i>Example</i>	<i>Detect and observe volcanic activity</i>	<i>Change in-situ sampling rate based on forecast</i>	<i>Select observing strategy to improve hydrologic estimates</i>
<b>Functions</b>	Detect emergent event Deploy observation assets	Deploy observation assets Digest information sources	Design observation system Digest information sources
<b>Capabilities</b>	<ul style="list-style-type: none"> <li>• Responsiveness</li> <li>• Interaction</li> <li>• Dynamics</li> <li>• Adaptation</li> </ul>	<ul style="list-style-type: none"> <li>• Resource allocation</li> <li>• Coordination</li> <li>• Data assimilation</li> <li>• Prediction/ forecasting</li> </ul>	<ul style="list-style-type: none"> <li>• Platform selection</li> <li>• Coordination</li> <li>• Data assimilation</li> <li>• State estimation (belief)</li> </ul>

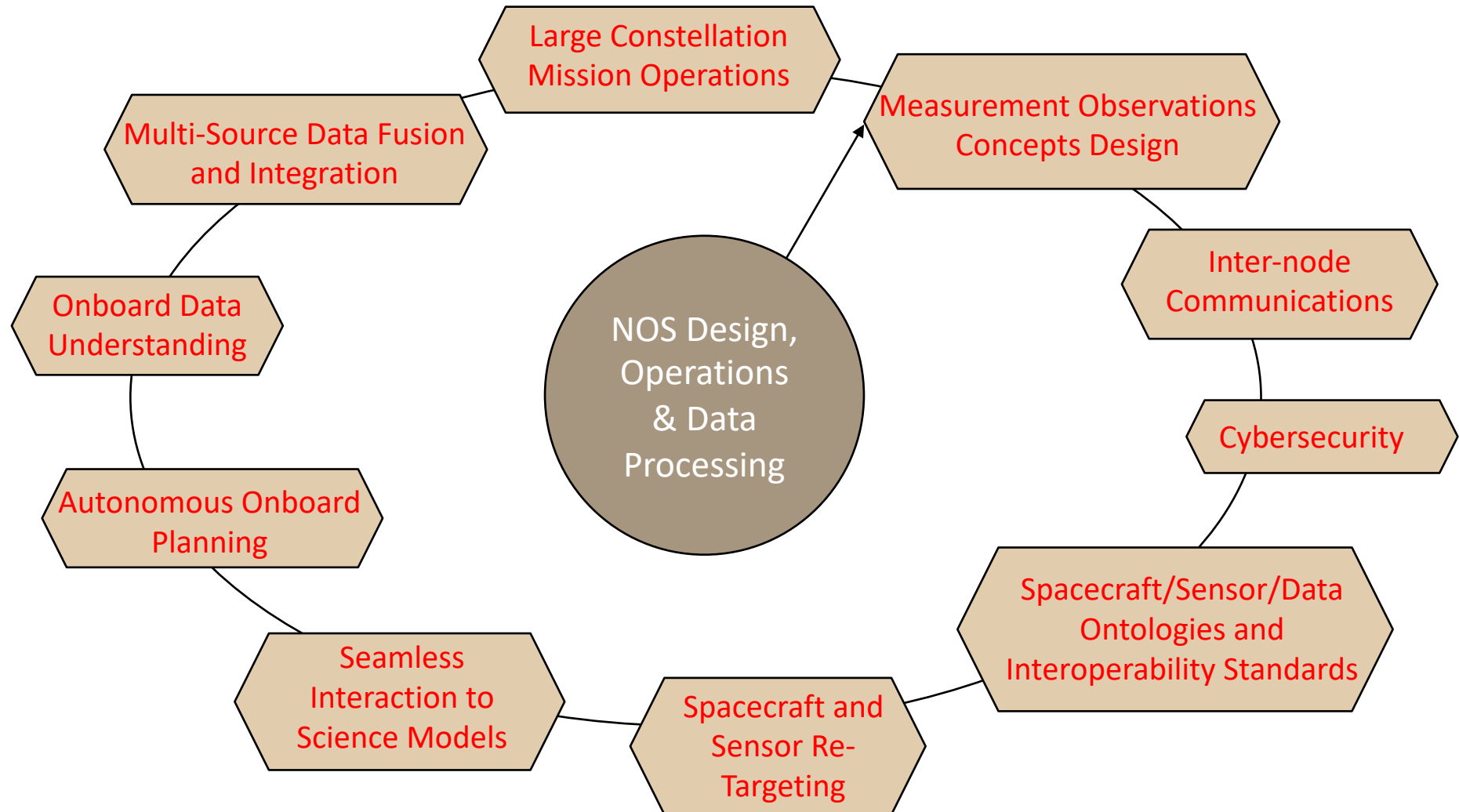
# NOS Concept for Hydrology => *for STV*



# Technologies Needed for NOS

## Some Examples of Capabilities Needed Onboard:

- Recognizing science events of interest
- Exchanging data inter-spacecraft
- Analyzing data for optimal science return
- Reconfiguring the spacecraft based on coordinated observations



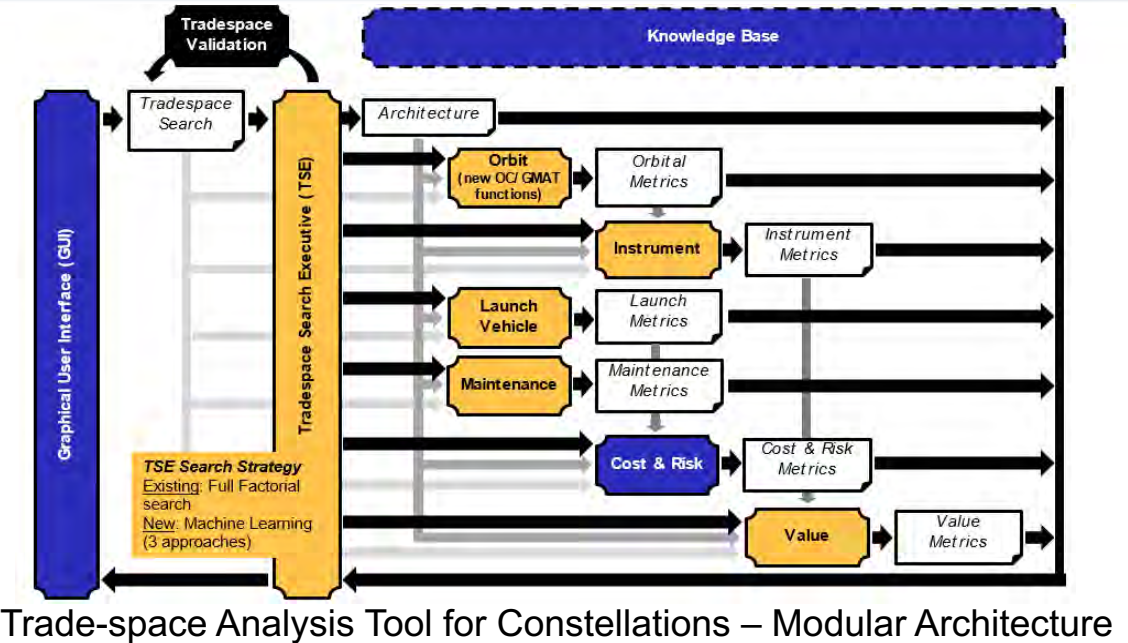
# NOS Technology: Constellation Design

*Trade-space Analysis Tool for Constellations (TAT-C); PI: Paul Grogan/SIT*



## Objectives

- Provide a framework to perform pre-Phase A mission analysis of Distributed Spacecraft Missions (DSM)
  - Handle multiple spacecraft sharing mission objectives, including sets of SmallSats up through flagships
  - Explore trade-space of variables (trajectories, orbital planes, instruments, launches, etc.) for pre-defined science, cost and risk goals, and metrics (e.g., spatial coverage, revisit frequency, etc.)
  - Optimize cost, risk and performance
- Optimize the trade-space exploration by utilizing Machine Learning and a fully functional Knowledge Base (KB)
- Create an open access toolset which optimizes specific science objectives by investigating various constellation architectures with improved efficiency, e.g., through parallelization
- **Government Release:**
  - <https://software.nasa.gov/software/GSC-18399-1>



## Approach

- Knowledge Base from historical constellation missions
- Novel mission architectures valuation
- Machine Learning (ML) knowledge-driven evolutionary strategies for fast traversal of large trade-spaces
- Instrument-level performance metrics for scanning optical imagers and SAR sensors
- Docker Container for Unix and non-Unix deployment

**Team:** P. Grogan/Stevens Institute of Technology; J. Verville, P. Dabney, S. Hughes/GSFC; S. Nag/BAERI; O. DeWeck, A. Siddiqi/MIT; D. Selva/Texas A&M – Current Extension: J. Johnson/OSU; M. French/USC-ISI

## Technical Readiness Level

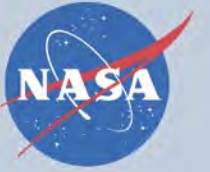
- Current Technical Readiness Level: TRL 5
- Currently being extended to include onboard computing as well as operations trades.
- Expected TRL of 6 in July 2021.
- Potential TRL of 8/9 in 5 years if resources available

## Challenges

- Enumeration of large number of potential architectures; extract essential constellation variables and trades
- Integrate in-situ and airborne trade considerations
- Beta testing and feedback from science community

# NOS System-of-System Validation

## *NOS Testbed Design and Demonstrations; ESTO Prototype Projects*



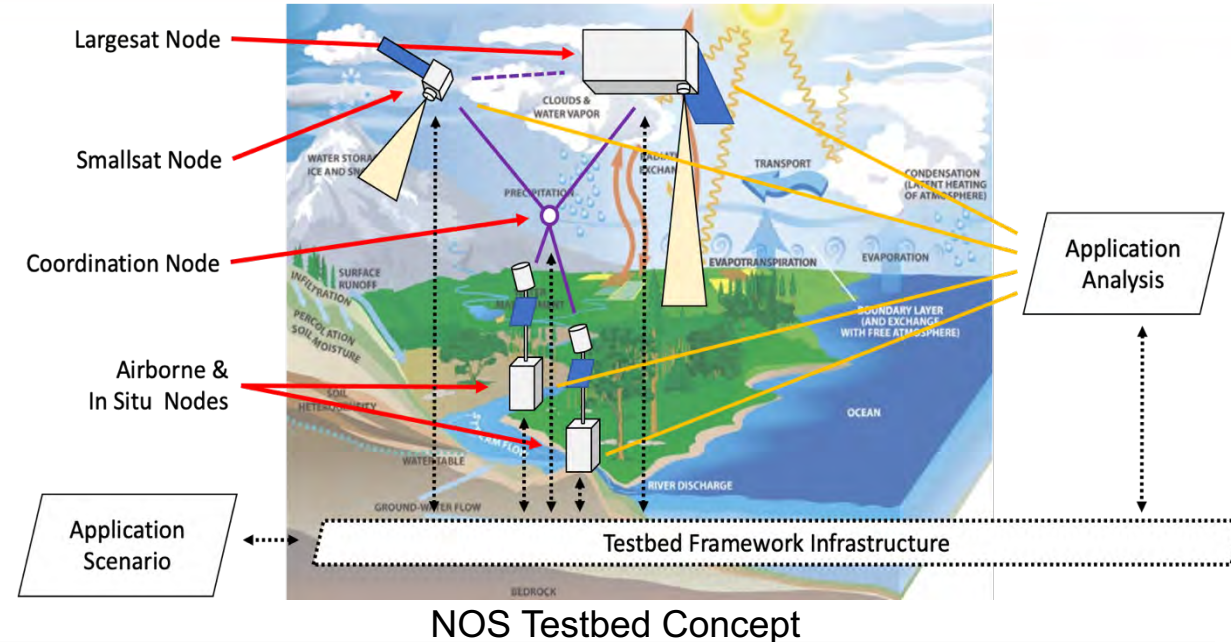
### **Objectives**

- New Observing Strategies (NOS) will optimize measurement acquisition using diverse observing capabilities, collaborating across multiple dimensions and creating a unified architecture.
- The Testbed Main Goals are to:
  1. Validate new NOS technologies, independently and as a system
  2. Demonstrate novel distributed operations concepts
  3. Enable meaningful comparisons of competing technologies
  4. Socialize new NOS technologies and concepts to the science community by significantly retiring the risk of integrating these new technologies.

### **Approach**

- Develop use cases corresponding to various science domains and 3 types of NOS scenarios – tactical, operational and strategic
- Design NOS-T framework architecture and interfaces
- Identify, develop and validate key NOS capabilities
- Conduct regular demonstrations

**Team:** P. Grogan, J. Sellers/SERC; I. Brosnan, D. Cellucci, C. Frost, N. Oza/ARC; S. Kumar/GSFC; S. Chien, D. Crichton, C. David, B. Smith/JPL; L. Rogers/LaRC; M. Cole, J. Ellis/KBR



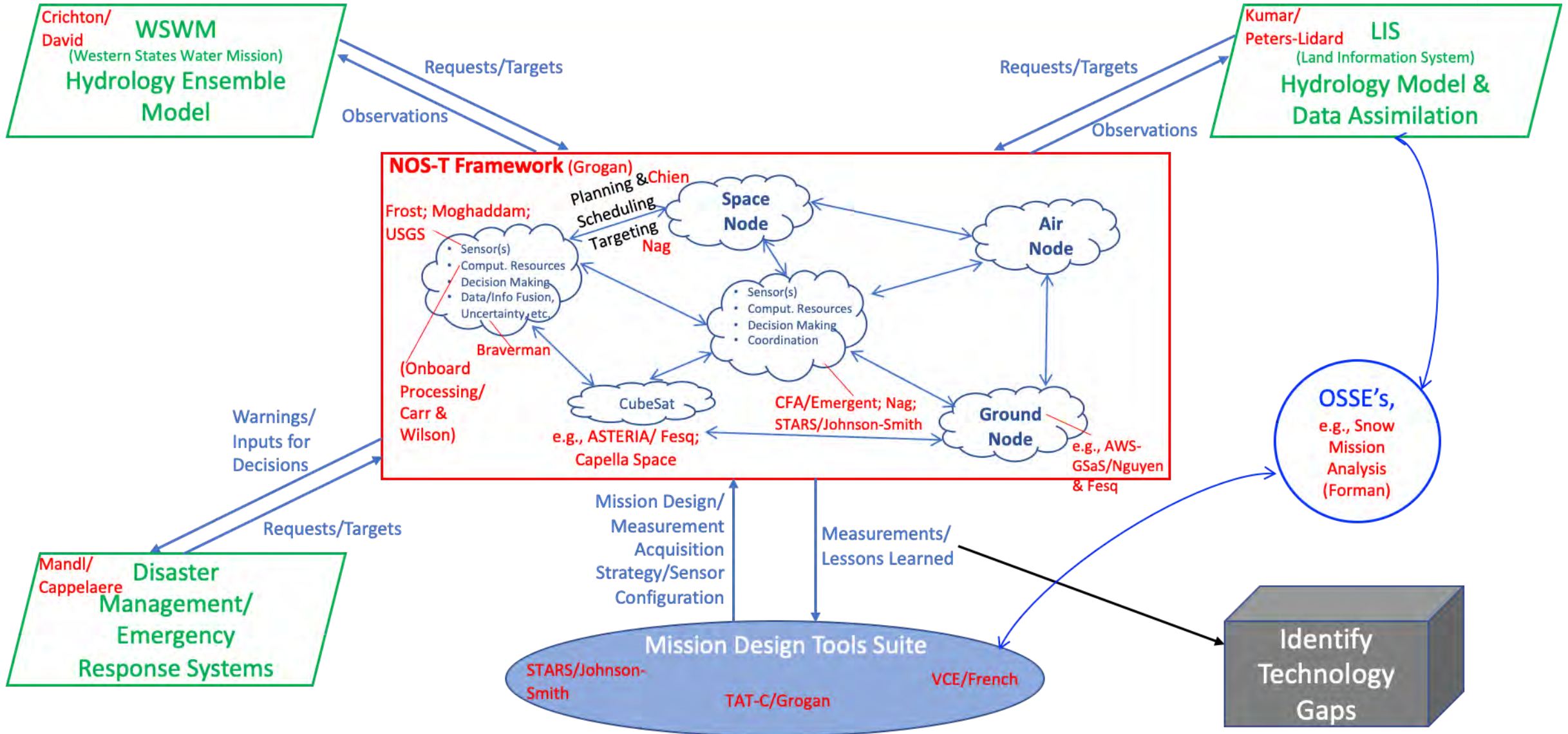
### **Technical Readiness Level**

- Current Technical Readiness Level TRL 2
- With current resources, expected TRL of 4 will be reached in FY21
- Potential TRL of 8 in 5 years if resources are available

### **Challenges**

- Identify all NOS required technologies
- Define and validate appropriate use cases
- Define appropriate, flexible and scalable standards and interfaces
- Gather wide community input and feedback

# NOS-Testbed Hydrology Concept



# AIST Awards – NOS Clusters



## • NOS-T Relevant

PI's Name	Organization	Title	Synopsis
Janice Coen	Univ. Corp for Atmospheric Research (UCAR)	Creation of a Wildland Fire Analysis: Products to enable Earth Science	Integrate multi-source data from various sensors and constellations from both public and private sectors for wildfire prediction and modelling.
Mahta Moghaddam	U. of Southern California	SPCTOR: Sensing Policy Controller and Optimizer	Multi-sensor coordinated operations and integration for soil moisture, using ground-based and UAVs "Sensing Agents".
Jim Carr	Carr Astro	StereoBit: Advanced Onboard Science Data Processing to Enable Future Earth Science	SmallSat/CubeSat high-level onboard science data processing demonstrated for multi-angle imagers, using SpaceCube processor and CMIS Instrument, and Structure from Motion (SfM).
Sreeja Nag	NASA ARC	D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions	Suite of scalable software tools - Scheduler, Science Simulator, Analyzer to schedule the payload ops of a large constellation based on DSM constraints (mech, orb), resources, and subsystems. Can run on ground or onboard.
Paul Grogan	Stevens Institute of Technology	Integrating TAT-C, STARS, and VCE for New Observing Strategy Mission Design	Inform selection and maturation of Pre-Phase A distributed space mission concept, by integrating: TAT-C: architecture enumeration and high-level evaluation (cost, coverage, quality); STARS: autonomous/adaptive sensor interaction (COLLABORATE); VCE: onboard computing and networking

## • OSSEs (Observing System Simulation Experiments)

PI's Name	Organization	Title	Synopsis
Derek Posselt	NASA JPL	Parallel OSSE Toolkit	Fast-turnaround, scalable OSSE Toolkit to support both rapid and thorough exploration of the trade space of possible instrument configurations, with full assessment of the science fidelity, using cluster computing.
Bart Forman	U. of Maryland	Next Generation of Land Surface Remote Sensing	Create a terrestrial hydrology OSSE/mission planning tool with relevance to terrestrial snow, soil moisture, and vegetation using passive/active microwave RS, LiDAR, passive optical RS, hydrologic modeling, and data assimilation, using LIS and TAT-C.
Ethan Gutmann	UCAR	Future Snow Missions: Integrating SnowModel in LIS	Improve NASA modeling capabilities for snow OSSE, to plan and operate a future cost-effective snow mission by coupling the SnowModel modeling system into NASA LIS.

# NOS-T Architecture and Pilot Projects



PI's Name	Organization	Emails	Title	Synopsis
Tom McDermott & Paul Grogan & Jerry Sellers	Systems Engineering Research Center (SERC)	tmcdermo@stevens.edu; pgrogan@stevens.edu; jsellers@tsti.net	New Observing Strategies Testbed (NOS-T) Design and Development	Design the NOS-T framework to enable system-of systems experiments and testing; enable multi-party and geographically distributed participation and connected tests and operations; enables both open community and protected exchange of measurement data; provide a communications infrastructure; and simulate actual operational security challenges.
Chad Frost & Daniel Cellucci	NASA Ames	chad@nasa.gov; daniel.w.cellucci@nasa.gov	Earth Science "Tip and Cue" Technologies for a New Observing Strategy	Extend the capabilities of the Generalized Nanosatellite Avionics Testbed (G-NAT) and networked, state-of-the-art, miniaturized, tracking and sensing devices (termed 'tags'), developed in collaboration with USGS, to enable a tip-and-cue architecture for dynamically reconfigurable remote sensing.
Sujay Kumar & Rhae Sung Kim	NASA Goddard	sujay.v.kumar@nasa.gov; rhaesung.kim@nasa.gov	A Hydrology Mission Design and Analysis System (H-MIDAS)	Extend LIS capabilities to: support the incorporation of distributed sensor observations for hydrology; support the development of observation operators; perform data assimilation simulations and provide feedback to the observing systems.
Steve Chien & James Mason	NASA JPL	steve.a.chien@jpl.nasa.gov; james.mason@jpl.nasa.gov	Planning and Scheduling for Coordinated Observations	Develop a planning and scheduling framework for the NOS Testbed that will coordinate multiple observing assets (e.g. space, air, land) to perform coordinated and continuous measurements at varying scales (e.g. spatial, temporal).
Dan Crichton & Cedric David	NASA JPL	daniel.j.crichton@jpl.nasa.gov; cedric.david@jpl.nasa.gov	NOS Testbed Study and Science Use Cases Identification	Contribute to the definition of the NOS Testbed by identifying science use cases, observing assets, requirements, interfaces, and other design recommendations in close collaboration with the NOS Testbed Definition activity.
Louis Nguyen	NASA LaRC		Ground Stations as a Service (GSaS) for Near Real-time Direct Broadcast Earth Science Satellite Data	Utilize GSaS to receive direct broadcast (DB) data from EOS to significantly reduce latency issue associated with acquiring LEO satellite observations. It will provide ability to receive low latency LEO data without the need to own/maintain DB ground station; reduce typical LEO Data Latency from 3-6 hours to 20-25 mins; improve NASA Earth Science's ability to deliver lower latency products to its communities and therefore increasing optimal use; provide NOS with capability to schedule, coordinate, receive, and process DB data from EOS
Jay Ellis	KBR/GSFC	nathaniel.j.ellis@nasa.gov	NOS Testbed Administration and Management	Administer and manage the NOS Testbed for disparate organizations to propose and participate in developing NOS software and information systems technology capabilities and services.

# Some References



## TAT-C:

- Le Moigne J., P. Dabney, O. de Weck, V. Foreman, P. Grogan, M. Holland, S. Hughes, S. Nag (2017). "Trade-space Analysis Tool for Designing Constellations," 2017 IEEE International Geoscience and Remote Sensing Symposium, July 23-28, Fort Worth, TX.
- Foreman V., J. Le Moigne, O. de Weck (2016). "A Survey of Cost Estimating Methodologies for Distributed Spacecraft Missions," *American Institute of Aeronautics and Astronautics (AIAA) SPACE 2016*, Long Beach, CA, September 13-16, 2016.
- Forman B., S. Kumar, J. Le Moigne and S. Nag (2017). "Towards the Development of a Global, Satellite-based, Terrestrial Snow Mission Planning Tool," 74th Eastern Snow Conference, June 6-8, Ottawa, Canada.
- Grogan P.T., P. Dabney, O. de Weck, V. Foreman, M. Holland, S. Hache, S. Hughes, J. Le Moigne, S. Nag, A. Siddiqi (2017). "Knowledge Base for Distributed Spacecraft Mission Design using the Trade-space Analysis Tool for Constellations (TAT-C)," 2017 Earth Science Technology Forum, June 13-15, Pasadena, CA.
- Hitomi, N., D. Selva (2018). "Constellation optimization using an evolutionary algorithm with a variable-length chromosome," 2018 IEEE Aerospace Conference, Big Sky, MT.
- Siddiqi A. and J. Le Moigne (2018). "Evaluating Expected Performance and Graceful Degradation in Distributed Spacecraft Missions," 2018 IEEE International Geoscience and Remote Sensing Symposium, July 22-27, Valencia, Spain.
- Nag, S., V. Ravindra, J.J. LeMoigne (2018). "Instrument Modeling Concepts for Tradespace Analysis of Satellite Constellations", IEEE Sensors Conference, Oct. 28-31, Delhi, India.
- Portelli, L., M. Sabatini, and P.T. Grogan (2019). "Ontology Development for Knowledge-driven Distributed Space Mission Systems Engineering," AIAA Science and Technology Forum and Exposition 2019, January 7-11, San Diego, CA.

## NOS and NOS-T:

- Le Moigne J., M. Little and M. Cole (2019). "New Observing Strategy (NOS) for Future Earth Science Missions," 2019 IEEE International Geoscience and Remote Sensing Symposium, IGARSS'19, Yokohama, Japan, July 28-August 2, 2019.
- Little M., J. Le Moigne and M. Cole (2019). "Testbed Requirements to Enable New Observing Strategies," 2019 IEEE International Geoscience and Remote Sensing Symposium, IGARSS'19, Yokohama, Japan, July 28-August 2, 2019.
- **IGARSS'2020 Invited Session on "Global Sensing through New Observing Strategies for Local Solutions" (TH2.R17):**
  - "Leveraging Space and Ground Assets in a SensorWeb for Scientific Monitoring", S. Chien et al
  - "Coordinating Observation at Global and Local Scales: Service-Oriented Platform to Evaluate Mission Architectures", P. Grogan et al
  - "D-Shield: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions", S. Nag et al
  - "SPCTOR: Sensing Policy Controller and Optimizer", M. Moghaddam et al
  - "Emulating and Verifying Sensing, Computation, and Communication in Distributed Remote Sensing Systems", M. French et al
  - "An Innovative SpaceCube Application for Atmospheric Science", J. Carr et al

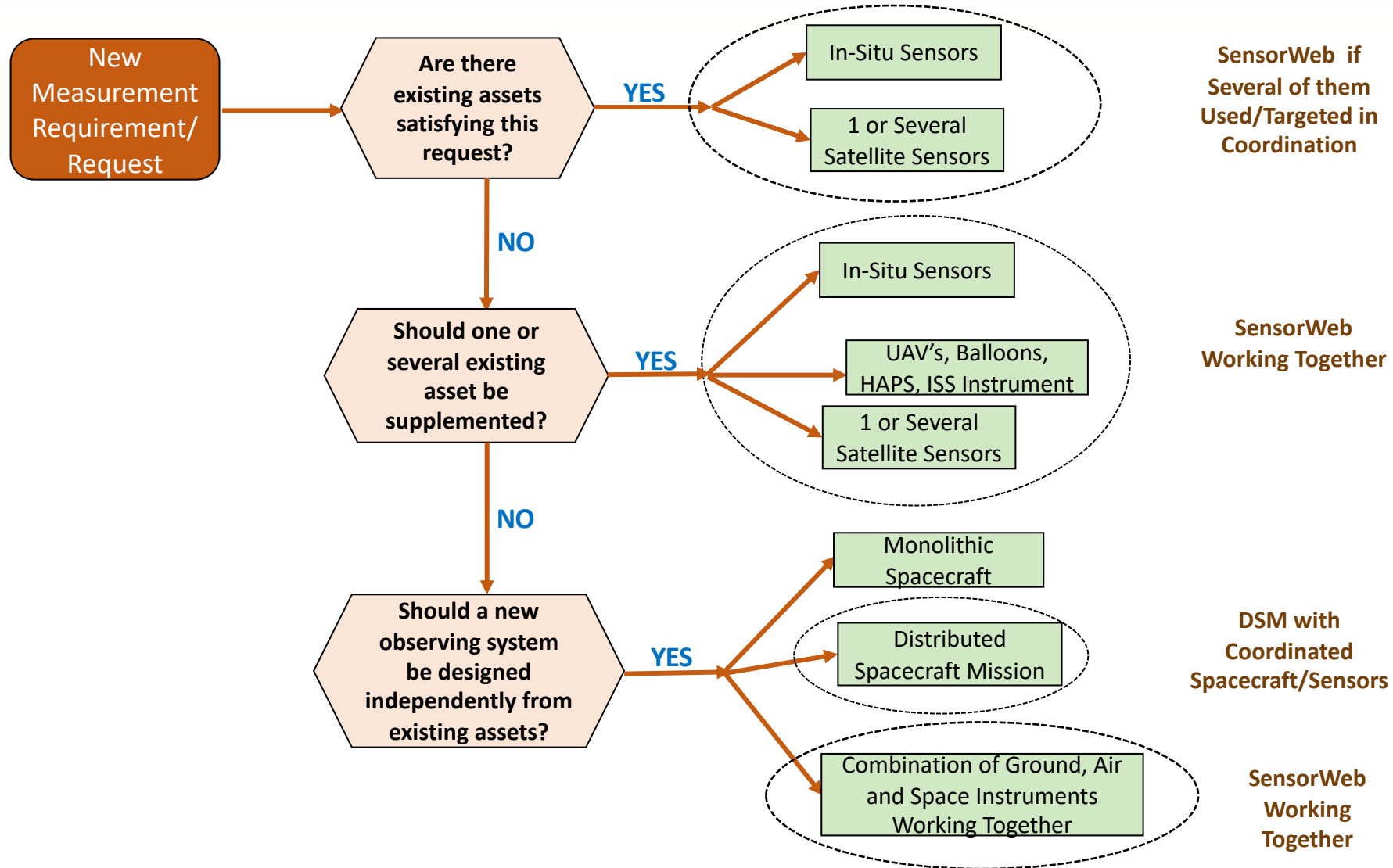


Any Questions?

# Back-Up Slides

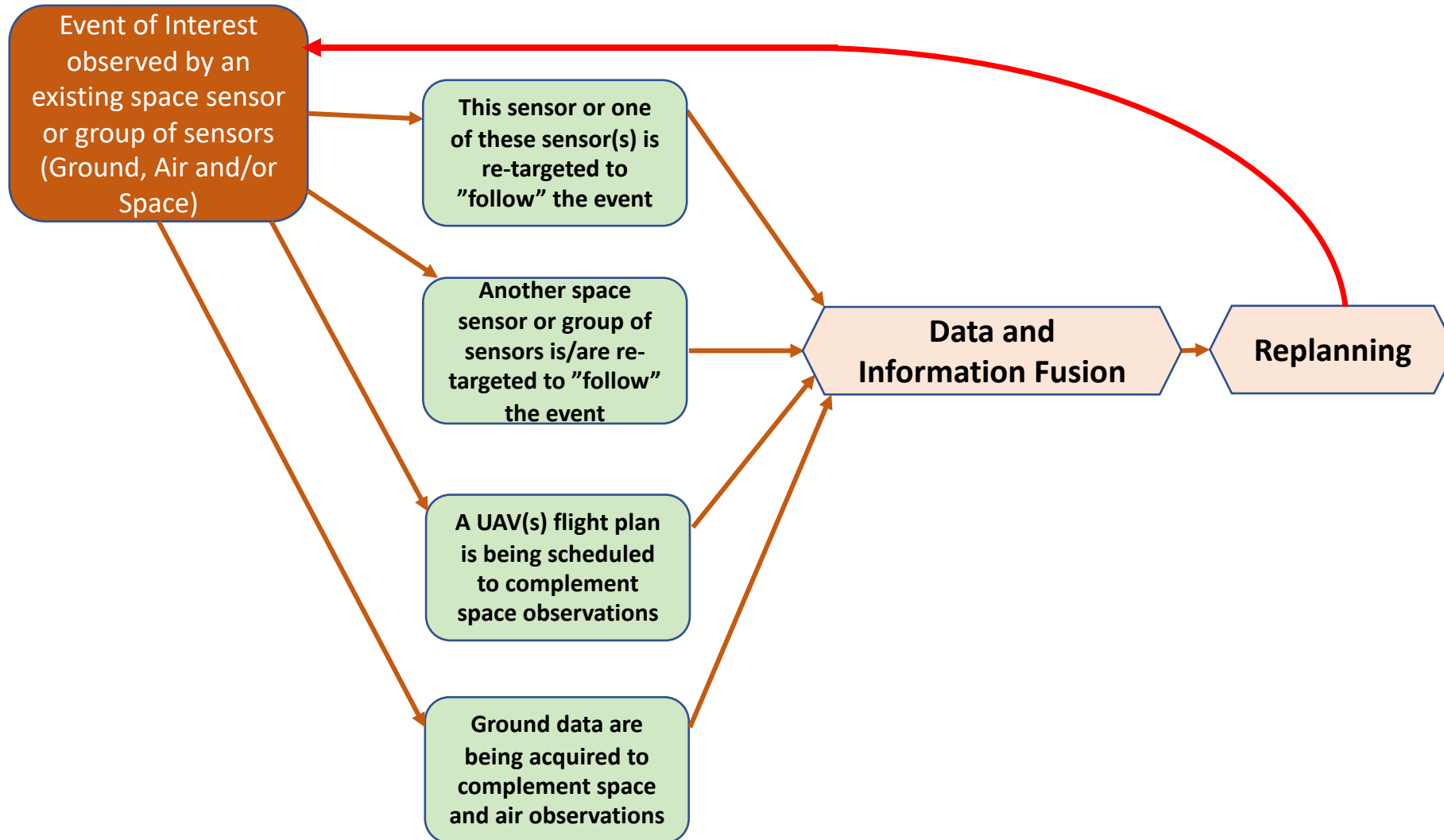
# New Observing Strategies (NOS)

## Measurement Acquisition (Observing System Design or Model-Driven)



# New Observing Strategies (NOS)

## *Observation Planning or Rapid Response to Event of Interest*



# Some Technologies Required for Intelligent and Collaborative Constellations (ICCs)



- **Onboard Processing**
  - High Performance Spaceflight Computing
  - Radiation-Hardened vs. Radiation Mitigation by Software (e.g., SpaceCube)
  - Neuromorphic Computing
- **Enabling and Supporting Technologies**
  - Multi-Spacecraft Flight Software
  - Real-Time and Onboard Image Processing and Analysis
  - Sensor Protocols and Secure Access
  - Semantic Representation (Bridge) of Disparate Observation Data
  - Precision Attitude Control Systems
- **Collaborative Systems Technology**
  - Dynamical and Fast Sensor/Inter-Spacecraft Communications
  - Sensor Fleet Management; Automated Tools for Mission Planning, Risk Analysis and Value Assessment
- **Knowledge Management for Decision Making**
  - Onboard Machine Learning and AI Technologies
  - Data/Information Fusion and Decision Systems



# NASA Ames Stereo Pipeline (ASP)



Ross Beyer – [ross.a.beyer@nasa.gov](mailto:ross.a.beyer@nasa.gov)

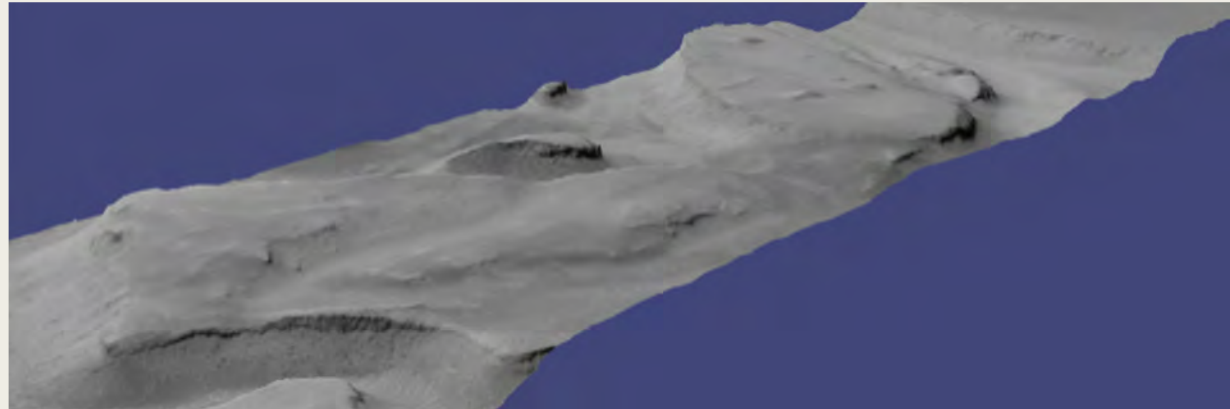
Oleg Alexandrov – [oleg.alexandrov@nasa.gov](mailto:oleg.alexandrov@nasa.gov)

Scott McMichael – [scott.t.mcmichael@nasa.gov](mailto:scott.t.mcmichael@nasa.gov)

David Shean - [dshean@uw.edu](mailto:dshean@uw.edu)

# What is the Ames Stereo Pipeline?

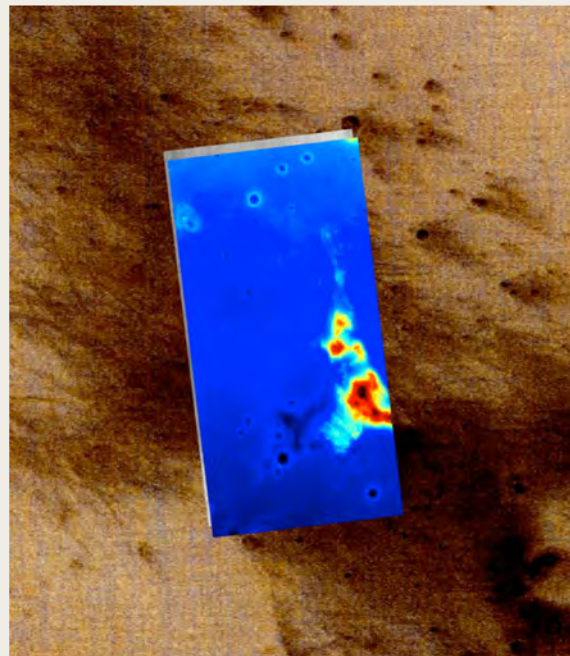
- A free, open-source software suite for working with stereo images.
- Easy to install on Linux and macOS.
- Additional tools for orthorectification, bundle adjustment, point cloud alignment, DEM mosaicking/compositing, shape-from-shading, and more.
- Designed for large-scale, automated processing (multi-thread/process).
- Support for orbiter stereo images since ~2008



Visualizing a DEM from the Mars Orbiter Camera (MOC)

# Supported Cameras

- Commercial VHR linescan/frame
  - DigitalGlobe/Maxar WorldView-1/2/3, GeoEye-1, Quickbird-2
  - Pleiades HR 1A/1B
  - Planet SkySat-C
- Satellite images with RPC metadata
  - Cartosat
  - Perusat
  - SPOT
- Non-terrestrial images (Moon, Mars, etc)
- Frame/Pinhole cameras (most aerial/UAV/consumer)
- Historical images (Hexagon, Corona)

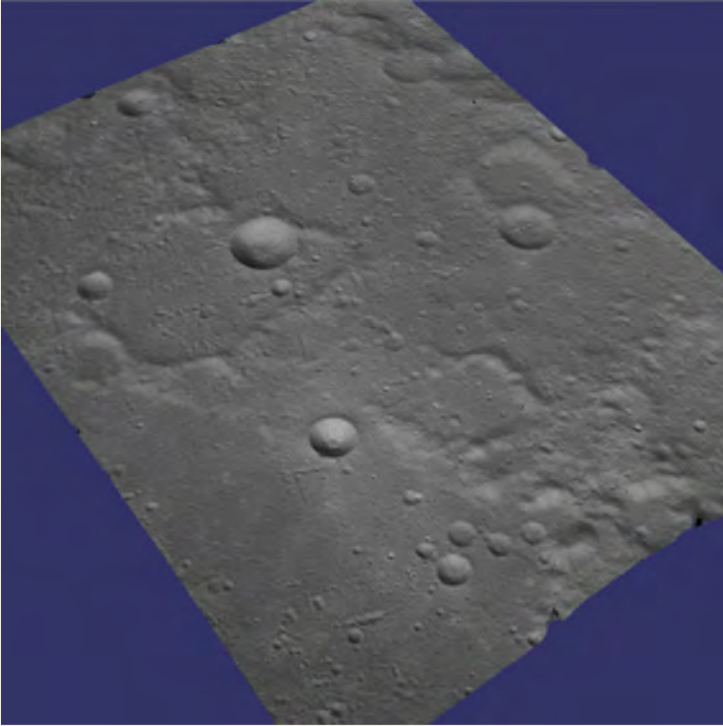


Colormap of DEM from HiRISE images shown in Google Earth

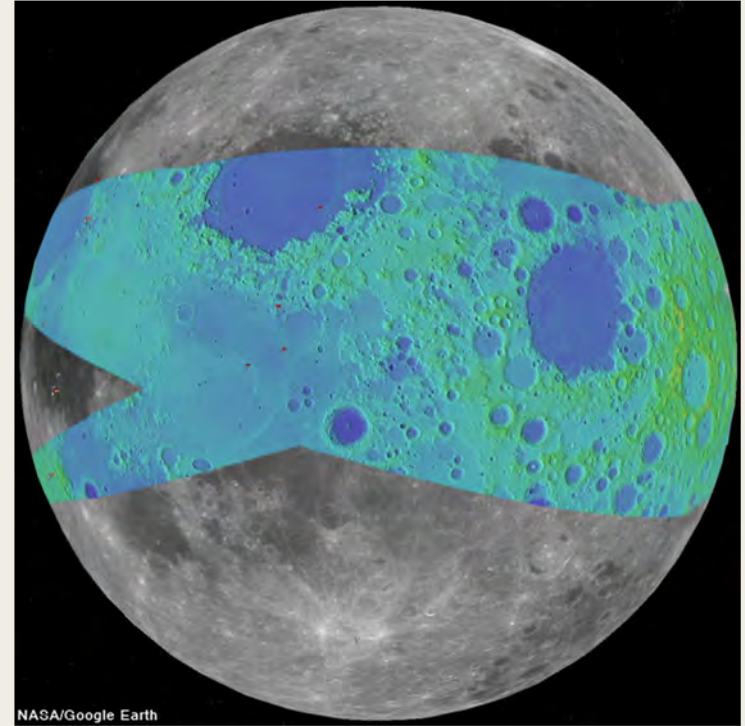
# Some notable projects with ASP

- Mosaic of over 4,000 Apollo camera images.
- DEM creation from eight years of NASA Operation Icebridge flights.
- Supporting VIPER rover landing sites for 2023 lunar mission using LRONAC images.
- Global glacier elevation change from declassified KH-9 HEXAGON images.
- DEM creation from over 1,000 LRONAC image pairs.
- Many projects using WorldView and Pleiades to study glacier and ice sheet change.

# Apollo mosaic

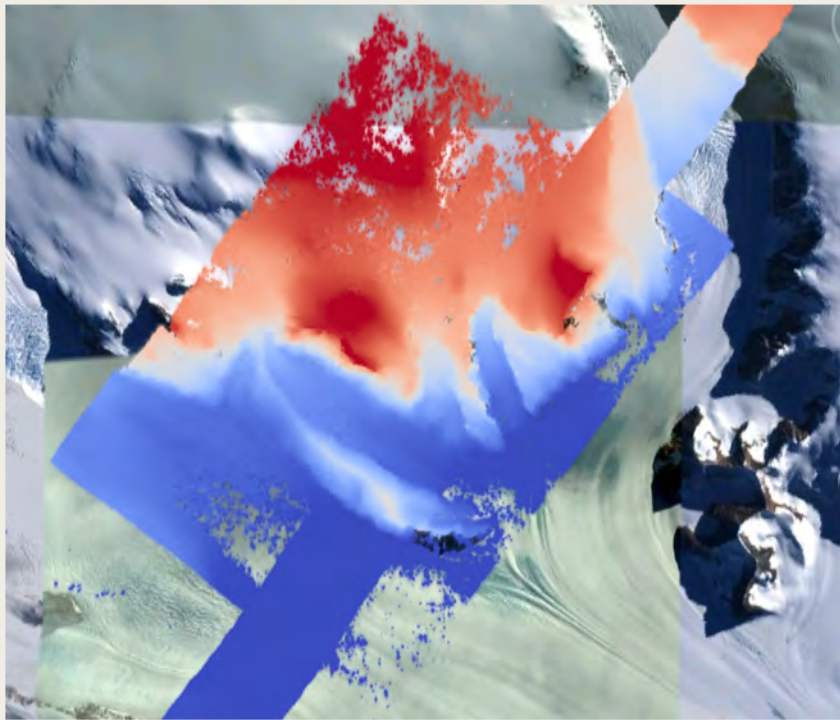


Hillshade from a sample metric camera pair



Color mapped view of the mosaic in Google Earth

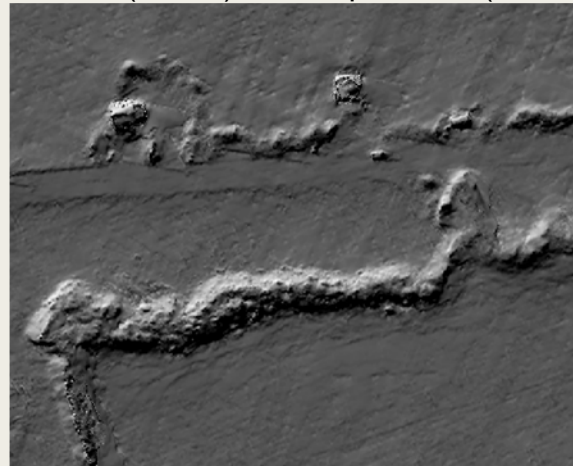
# NASA Operation IceBridge: DMS



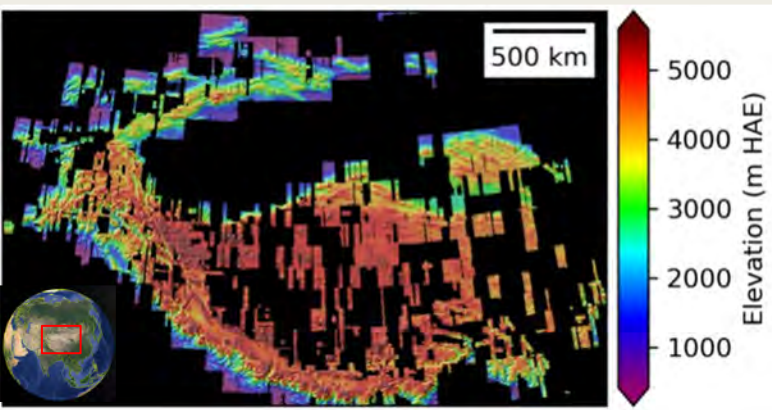
ASP DEM (wide) aligned with LIDAR DEM  
(narrow)



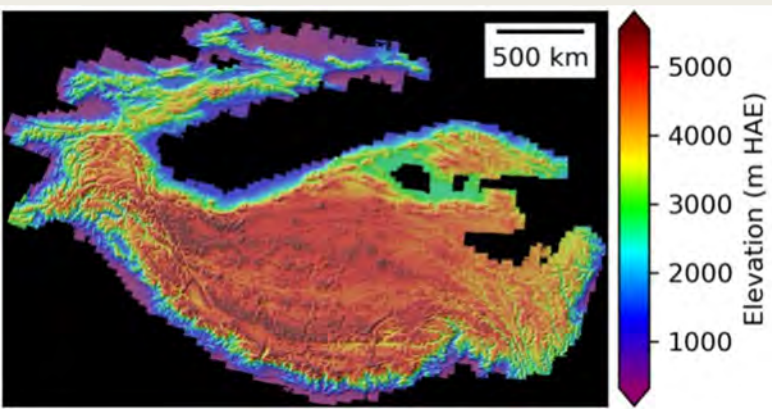
Sample image from Canon EOS 5D Mark II  
digital camera (above) and output DEM (below)



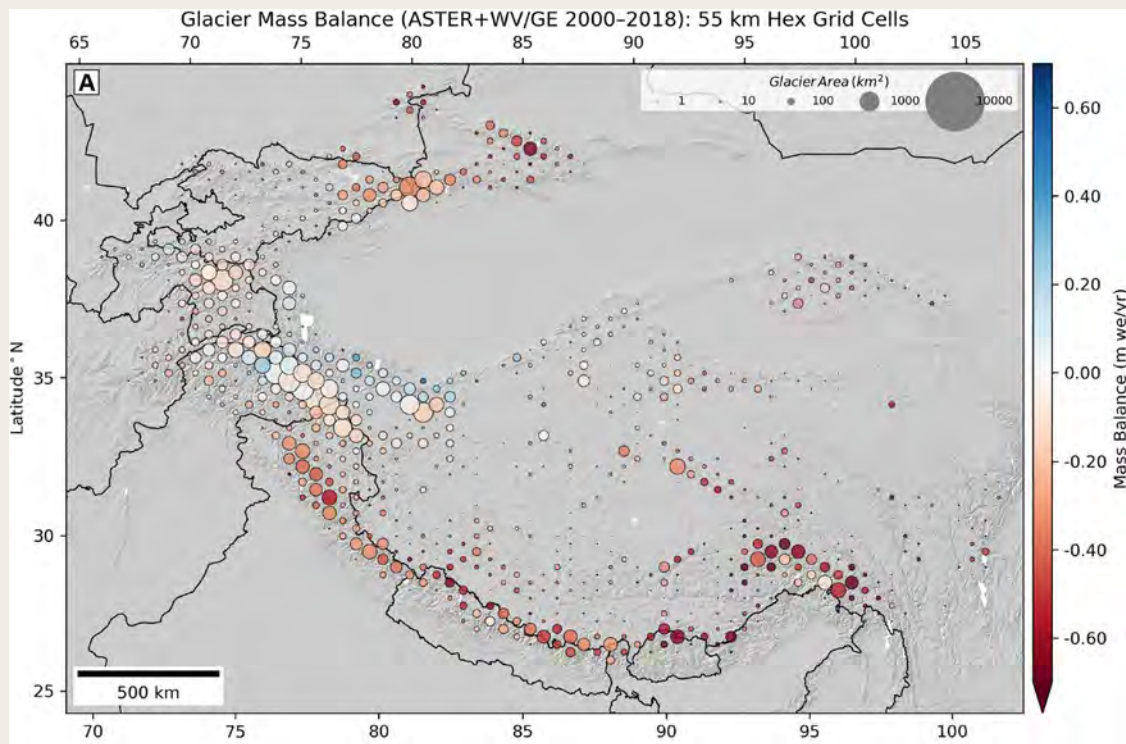
# High-Mountain Asia DEM and Glacier Mass Balance



WorldView/GeoEye (5524 DEMs)



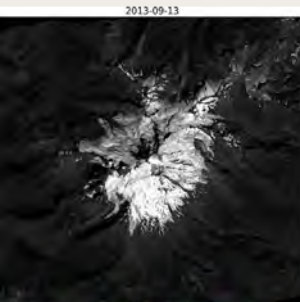
ASTER (27861 DEMs)



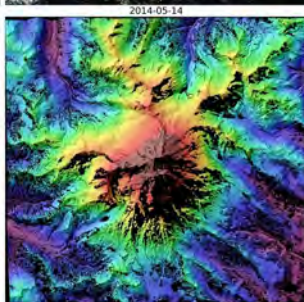
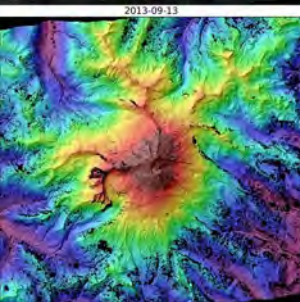
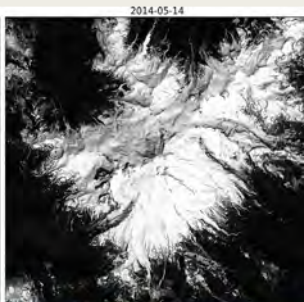
Shean et al. (2020), Frontiers

# Stereo2SWE - Snow depth from VHR stereo

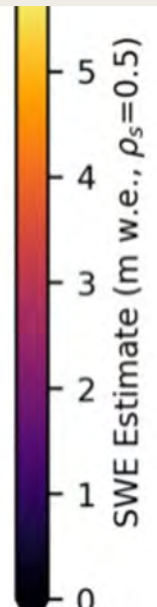
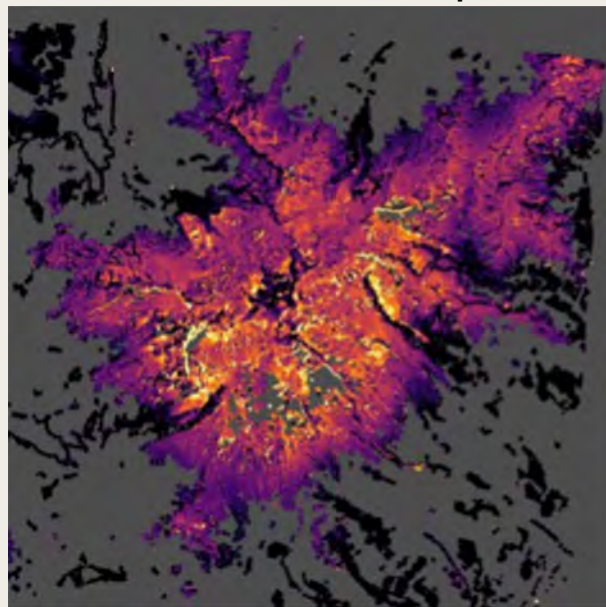
Snow-off



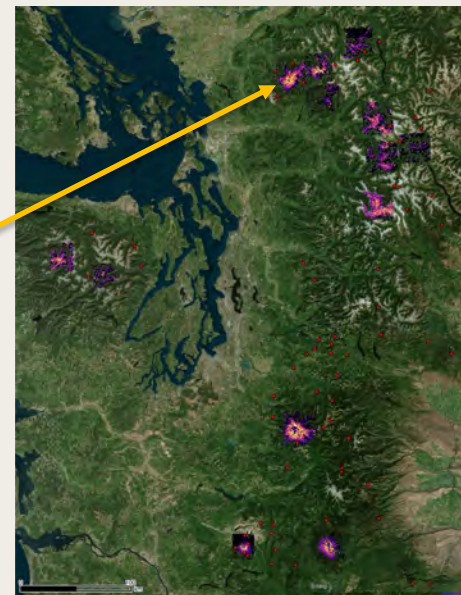
Snow-on



Snow depth



WY2016 Peak SWE



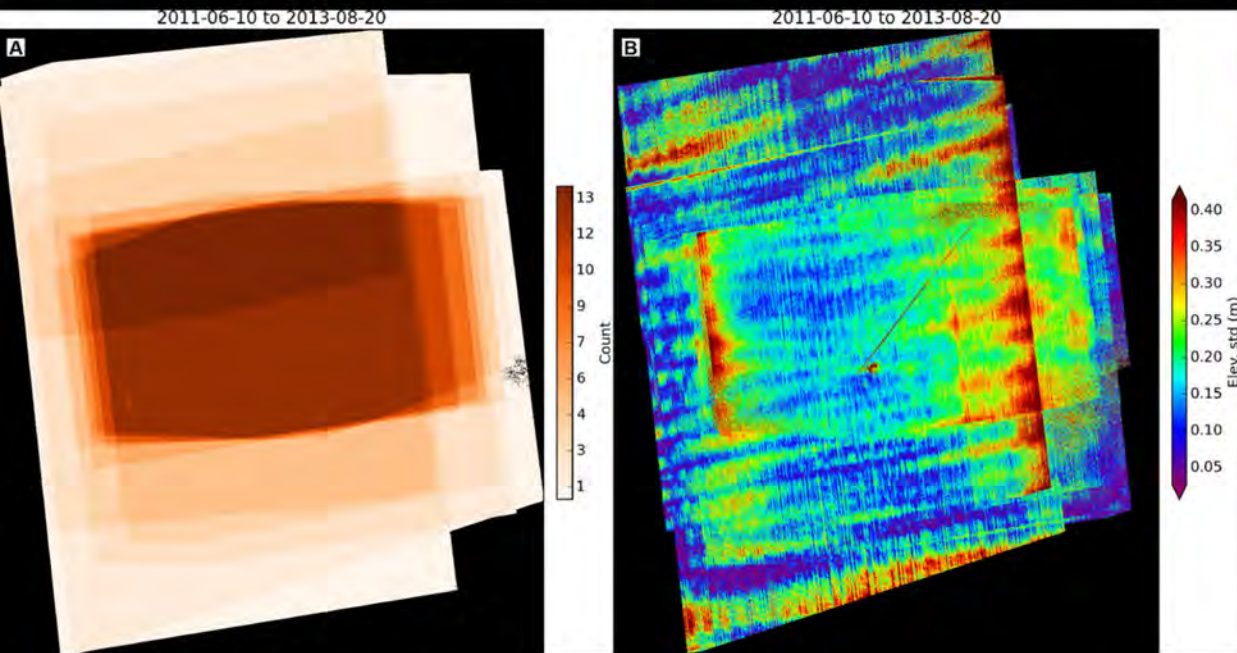
# Performance and Processing Time

- Most of the processing for a given image pair can be run in parallel.
  - Stereo processing can be easily spread across nodes in shared memory systems.
- Timing statistics on WV1/WV2 images:
  - Median 9 hours to process a single image (~ 36k by 220k pixels size).
  - Used a typical processing method including bundle adjustment and map projection.
  - Tested on single dual 6-core 2.93 GHz Intel Xeon X5670 nodes on the Pleiades supercomputer.
  - Shean et al. (2016), ISPRS Journal of Photogrammetry and Remote Sensing
  - Timing is heavily dependent on image quality and processing options.
- Automated workflow - no manual steps are required
- Users have processed thousands of images with ASP

# Accuracy and resolution

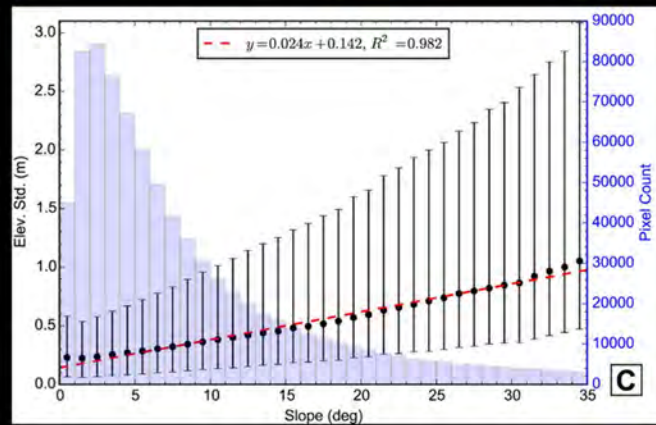
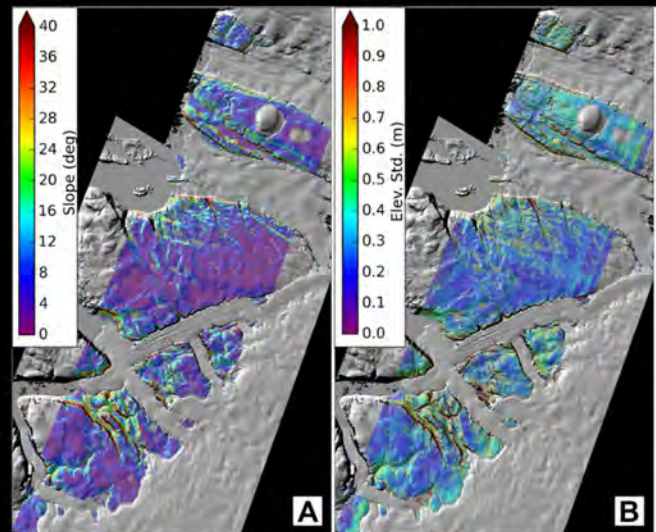
- Horizontal and Vertical accuracy depends on:
  - Image GSD, texture
  - Camera model accuracy
  - Stereo geometry
  - Surface slope, roughness
- ASP supports block matching, SGM, and MGM stereo algorithms
  - Performance is similar to other popular automatic stereo software
  - Different algorithms perform better in different situations
- ASP subpixel accuracy up to 0.2 pixels
- Options to improve accuracy:
  - Linescan “jitter” correction
  - Multi-view
  - Improved image alignment
  - Better sensor characterization
  - Incremental algorithm improvements (subpixel, point cloud alignment, etc)

# WV DEM Relative Error



Per-pixel stack count and standard deviation (n=14)  
Summit Station, Greenland (flat)

## Surface slope and per-pixel std (n=17)



# ASP development status

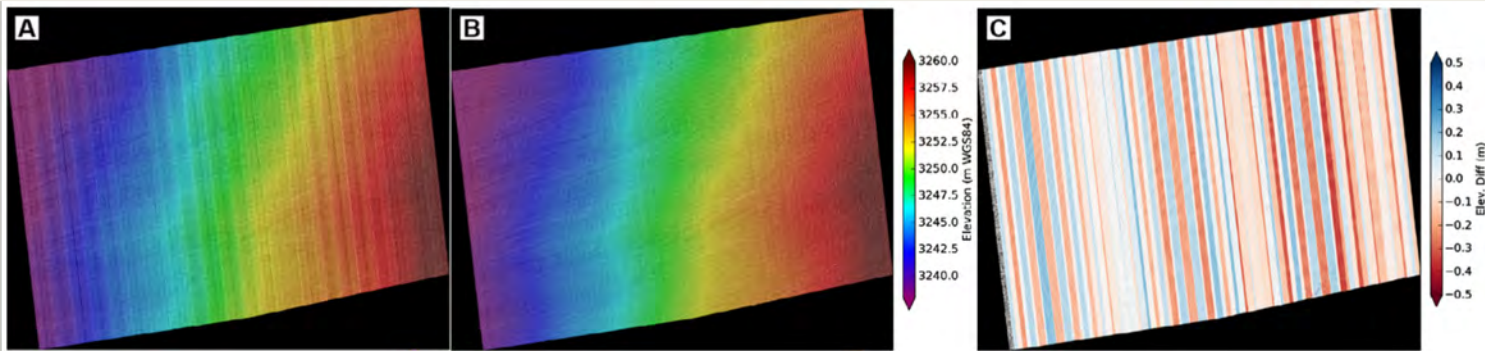
- ASP is not continually funded, usually we rely on (sporadic) funded proposals or funding from external researchers to implement specific features.
- Our last funded development included a revamp of our build system, support for the popular conda package manager, and improved documentation.



Left to right: A hill shaded DEM, the same DEM after shape-from-shading, the absolute difference between them.

# Future (funded!) plans

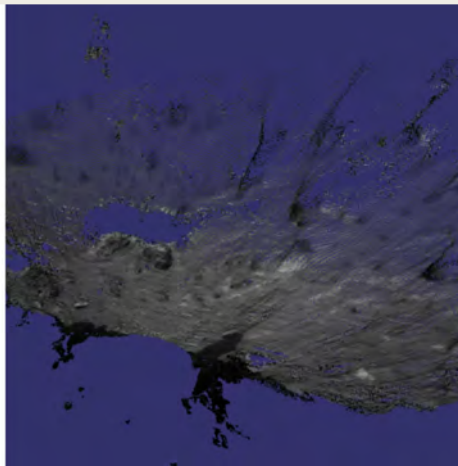
- Local image alignment (NASA PDART)
  - Break large images up into sub-images which are individually aligned for improved performance
- Plugin stereo algorithms (NASA PDART)
  - Much easier to add new stereo algorithms, but requires good vertical alignment
- Stereo-derived bathymetry (USGS CoNED)
- Improved sub-pixel artifact correction for Digital Globe/Maxar platforms (NASA THP)



WorldView CCD artifact correction

# Gaps and future development

- Better results for built terrain and terrain with vegetation
  - ASP was designed to work well on surfaces like the Moon and Mars
- Error reporting features such as per-pixel uncertainty values
- Improved multi-view triangulation
- Users are always requesting a variety of new features!

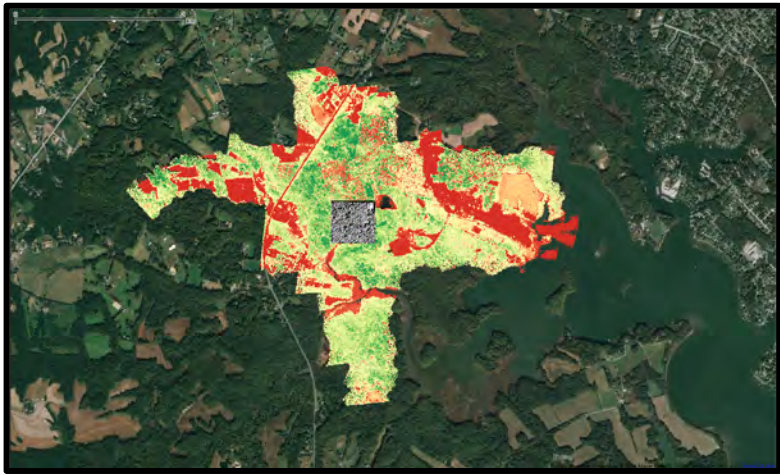


A Mars Exploration Rover image and a point cloud generated from it.

# Reference

- ASP Source code, binaries, and documentation are available at <https://github.com/NeoGeographyToolkit/StereoPipeline>
- Publications using ASP: <https://stereopipeline.readthedocs.io/en/latest/papersusingasp.html>
- ASP References: <https://stereopipeline.readthedocs.io/en/latest/zzreferences.html>
- NASA IceBridge ASP DEM page: <https://nsidc.org/data/IODEM3>

# Canopy surfaces & DSM variation with actual and simulated spaceborne stereopairs



*Towards understanding the sensitivity of spaceborne vegetation surface estimates using simulations of stereo image pairs and DSM processing with existing stereogrammetry workflows.*

Stereogrammetry workflow:  
[paul.m.montesano@nasa.gov](mailto:paul.m.montesano@nasa.gov)

DART simulations:

Contributors:  
[christopher.s.neigh@nasa.gov](mailto:christopher.s.neigh@nasa.gov)

[doug.morton@nasa.gov](mailto:doug.morton@nasa.gov)

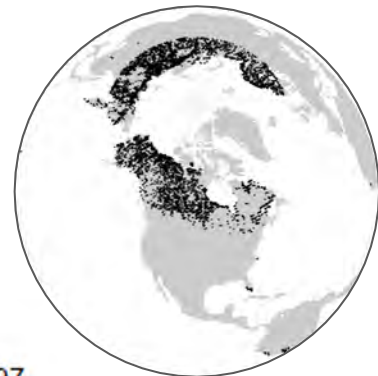
**Paul Montesano** |

**Tiangang Yin** | [tiangang.yin@nasa.gov](mailto:tiangang.yin@nasa.gov)

Chris Neigh |

Doug Morton |

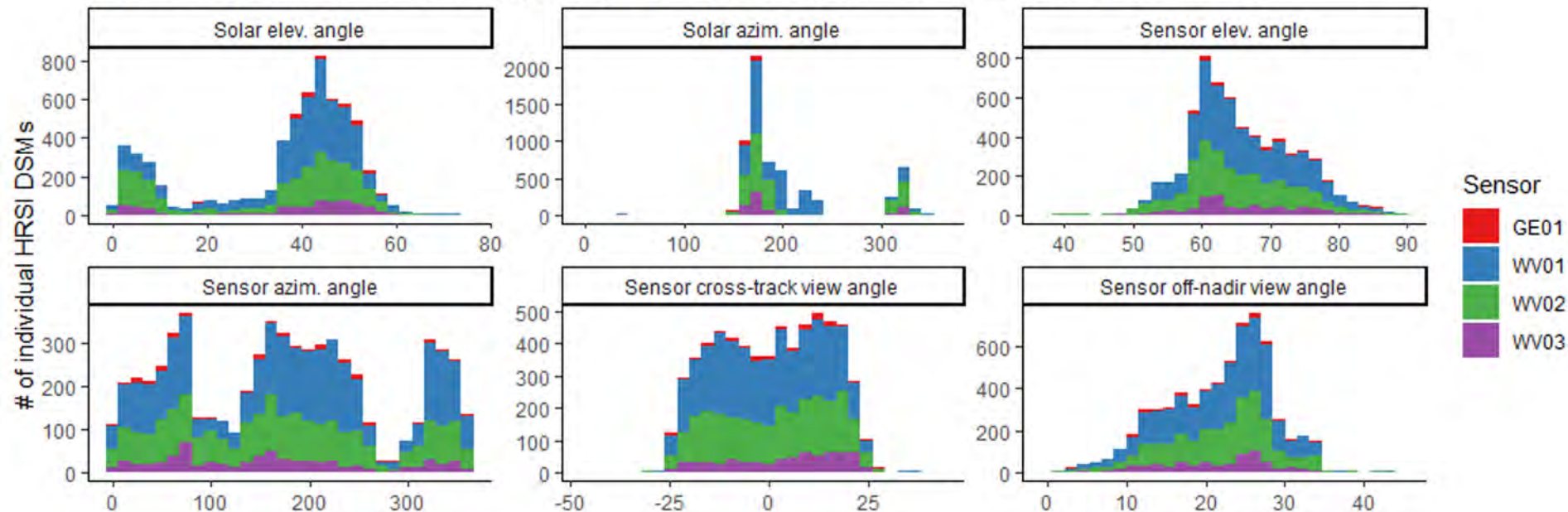
# A variety of spaceborne stereo acquisitions



*Acquisition characteristics of an archive of boreal DSMs from DigitalGlobe stereopairs*

## Boreal HRSI DSMs

The HRSI acquisition sun-sensor-target geometry of each processed DSM archived on NASA's ADAPT,  $n=6297$



# Variation difficult to study with spaceborne archive

*Example showing variations between acquisitions:*

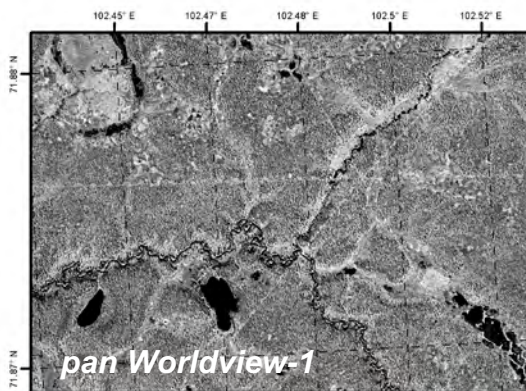
Where image variations OVERLAP, we can see differences in STV estimates

Montesano et al. 2017 (RSE)

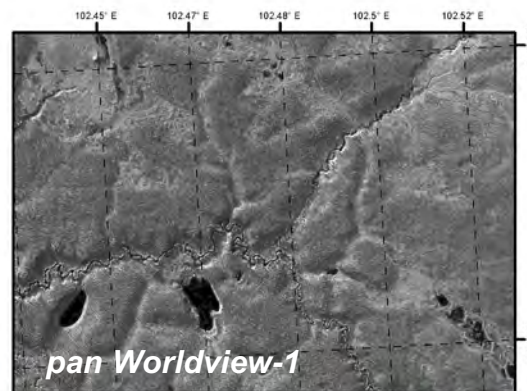
<https://doi.org/10.1016/j.rse.2017.04.024>

*The same sparse forest extent (captured 1 day apart), with different sun and view angles produce DSMs with different texture and surfaces.*

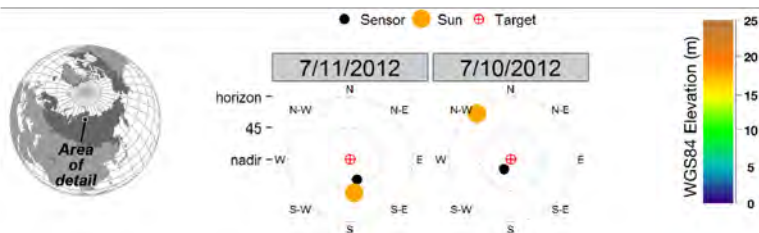
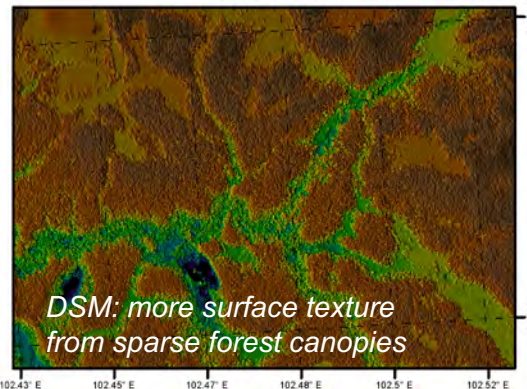
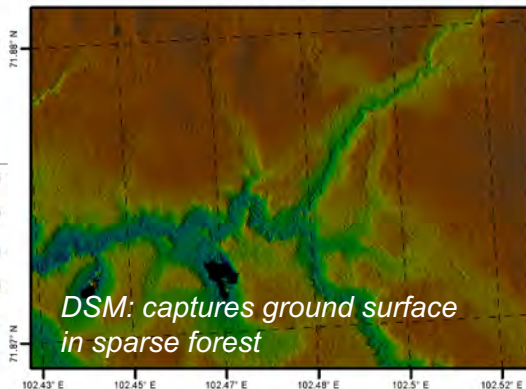
© MAXAR 2020 NextView License



7/11/2012



7/10/2012



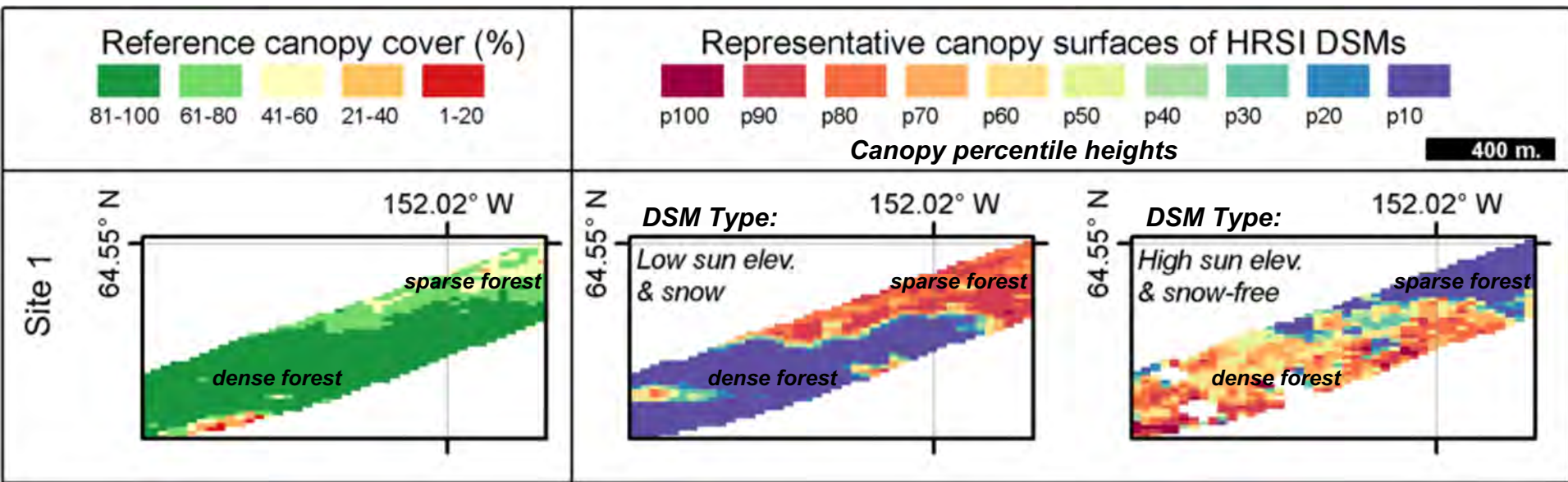
# Variation difficult to study with spaceborne archive

*Example show variation in boreal canopy surfaces represented in high resolution spaceborne image (HRSI) DSMs*

Montesano et al. 2019 (RSE)

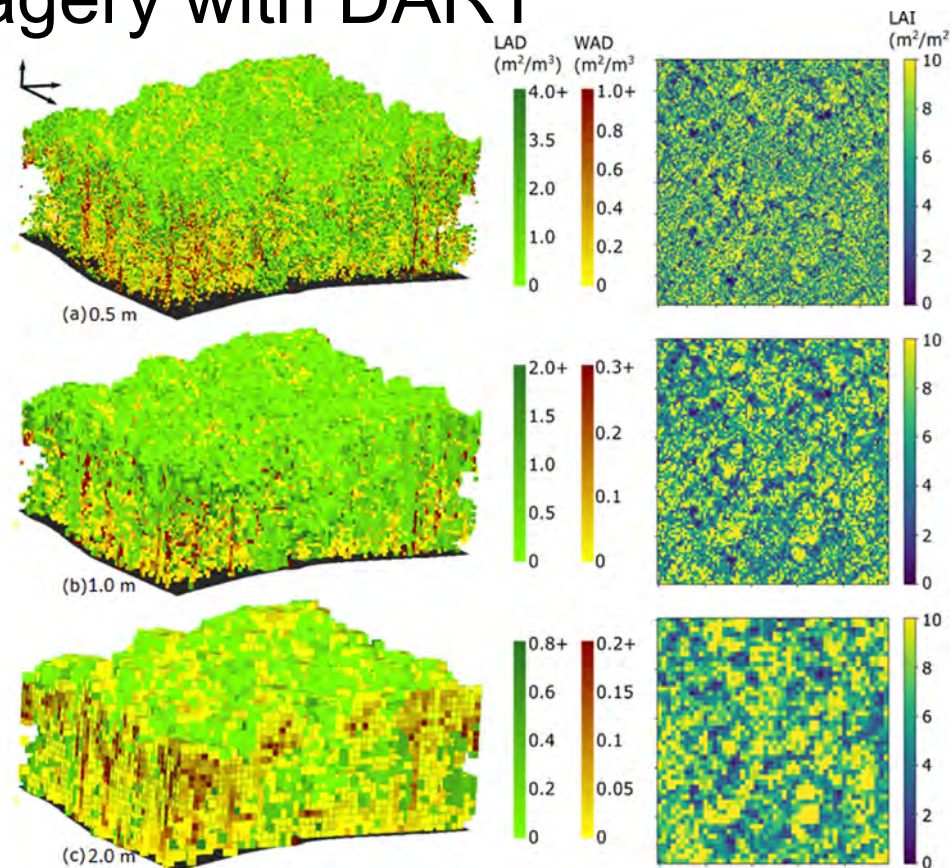
<https://doi.org/10.1016/j.rse.2019.02.012>

*Example below shows how vertical boreal canopy surfaces that are represented by different HRSI DSM types can vary significantly.*

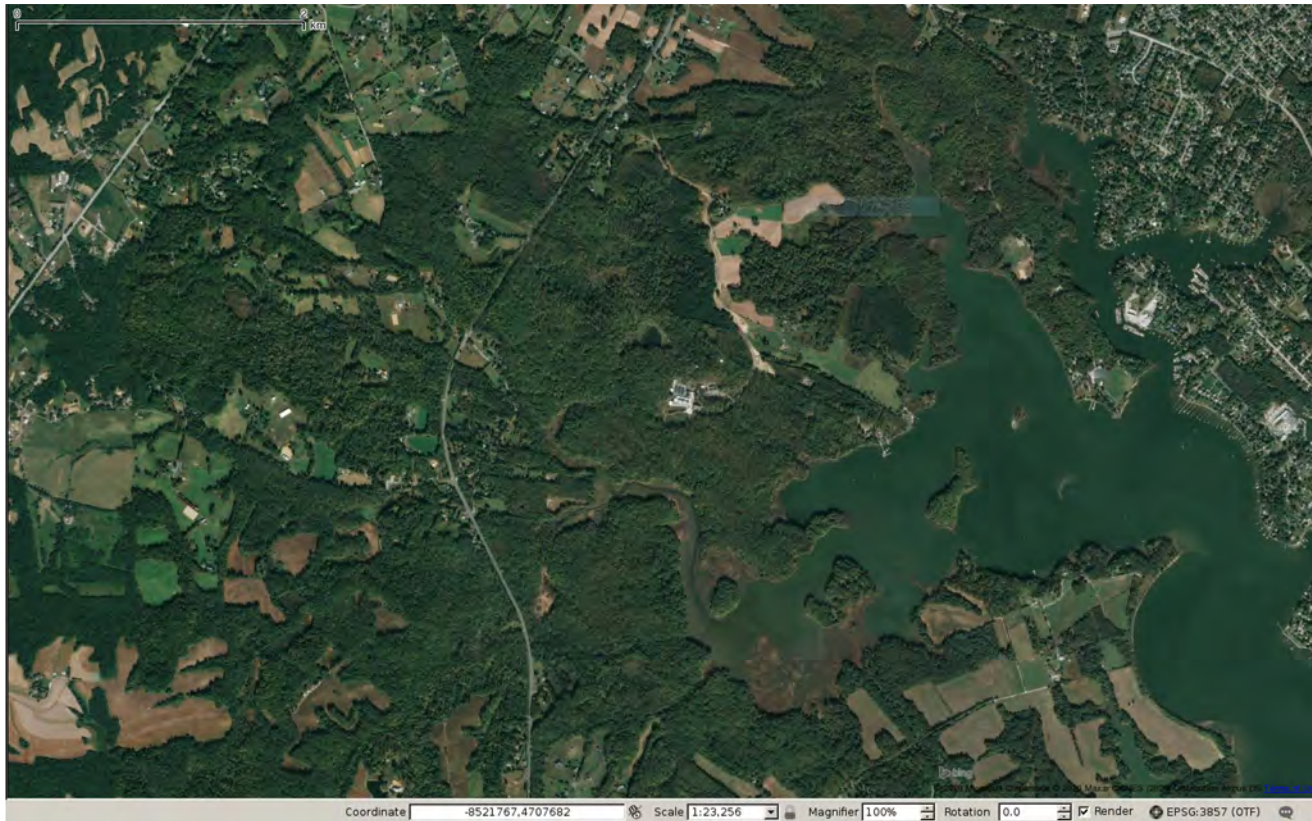


# Simulating spaceborne imagery with DART

- Multi-temporal (leaf-on and leaf-off, 2012) and multi-path acquisitions of G-LiHT
- Realistic 3-D voxel scene (0.5m, 1m, and 2m) constructed by ray tracing alone each return of every G-LiHT LiDAR pulses (~45 points per m<sup>2</sup>)
- 3-D distribution of Woody Area Density (WAD) and Leaf Area Density (LAD) retrieved
- LAI validated against litter-collection direct field measurements
- LAD reliability reduced from the top to the bottom of the canopy, which facilitates image simulation (majority signal comes from the top)



# Simulating spaceborne stereo imagery and DSMs



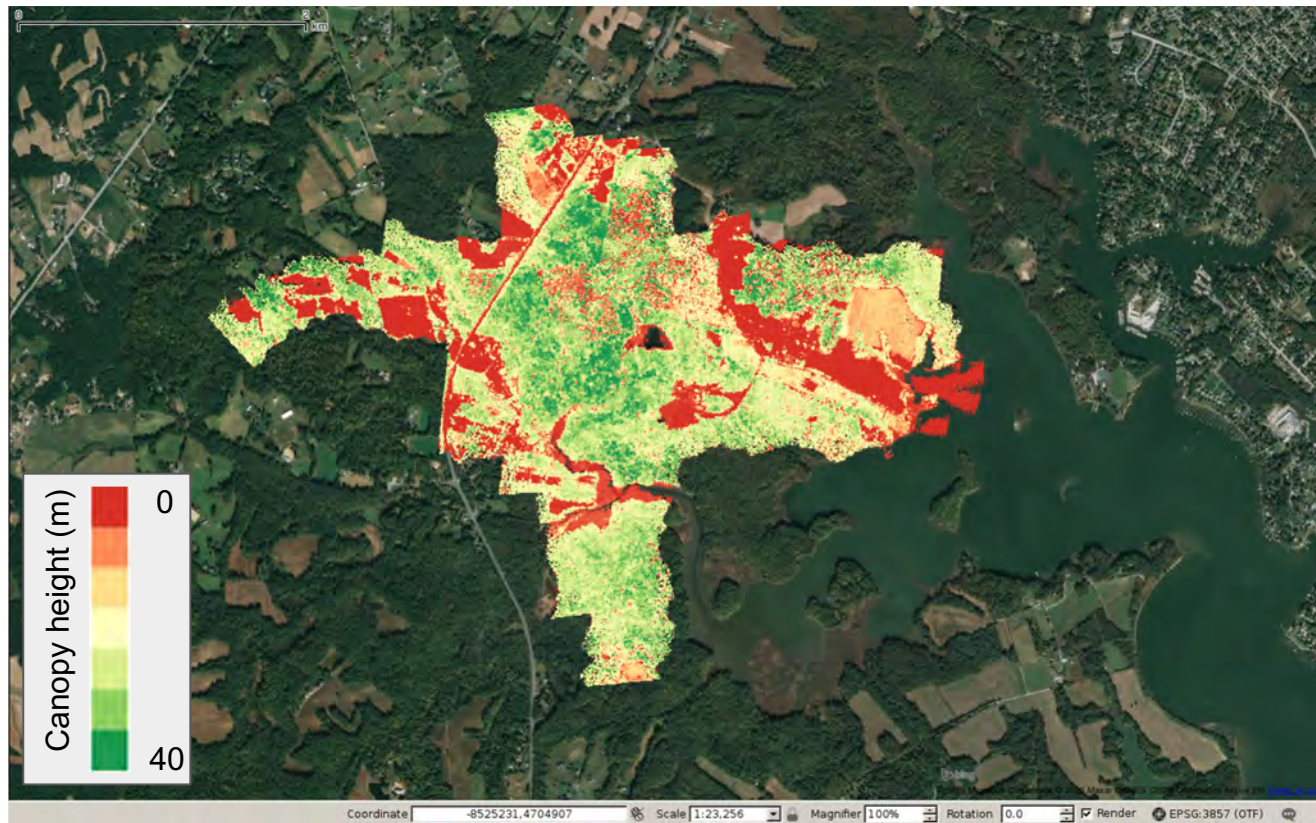
**Goal:** study STV errors in DSMs  
different image acquisitions

- *SERC: simulation site where DART uses field data to simulate forest structure*
- *DART simulates stereo image pairs*
- *Simulated stereo image pairs are processed to DSMs.*
- *DSMs are compared to GLiHT to uncertainty STV uncertainties.*

**Key to proving the concept:**

- *Ingesting DART simulations into current stereogrammetry workflows*

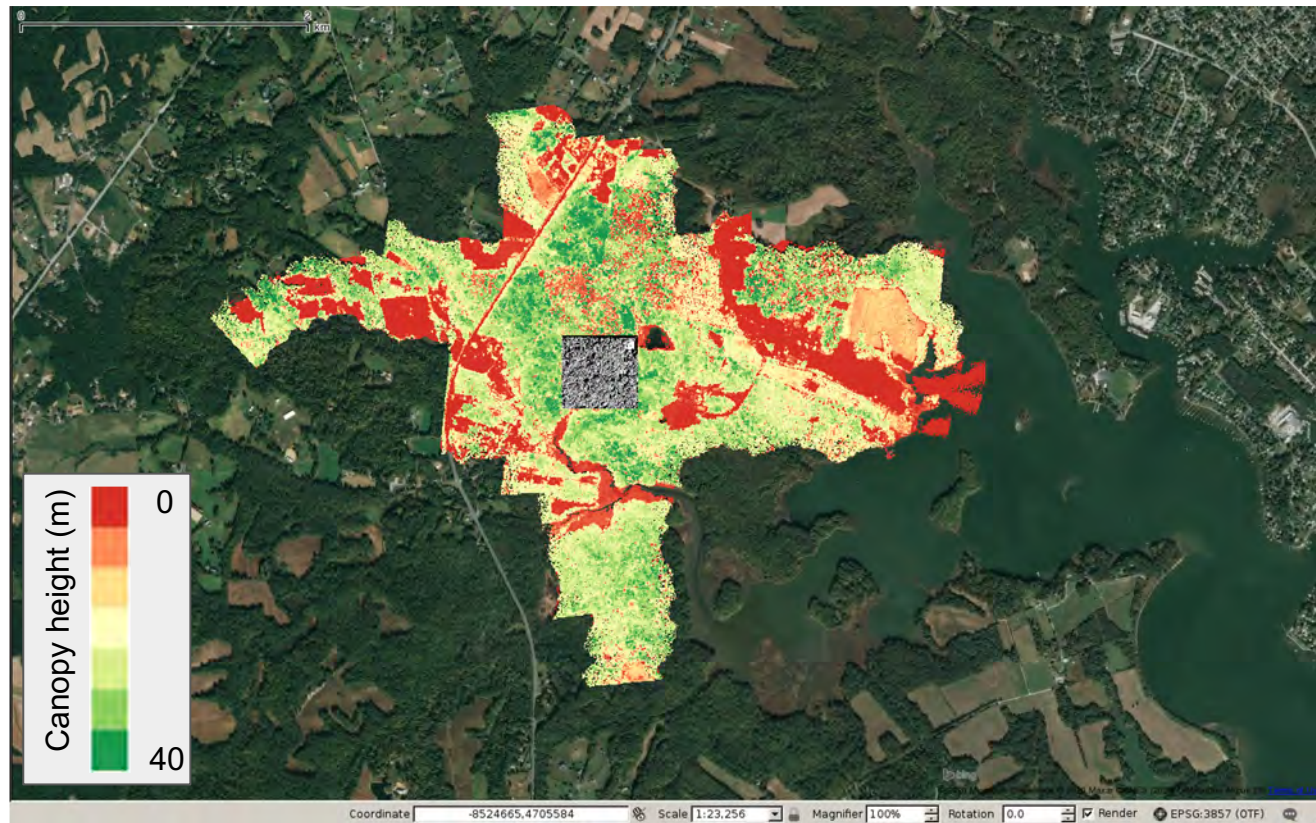
# Canopy height model from GLiHT



*Reference forest structure  
data*

*1 m pixels of canopy height*

# DART simulation extent within SERC

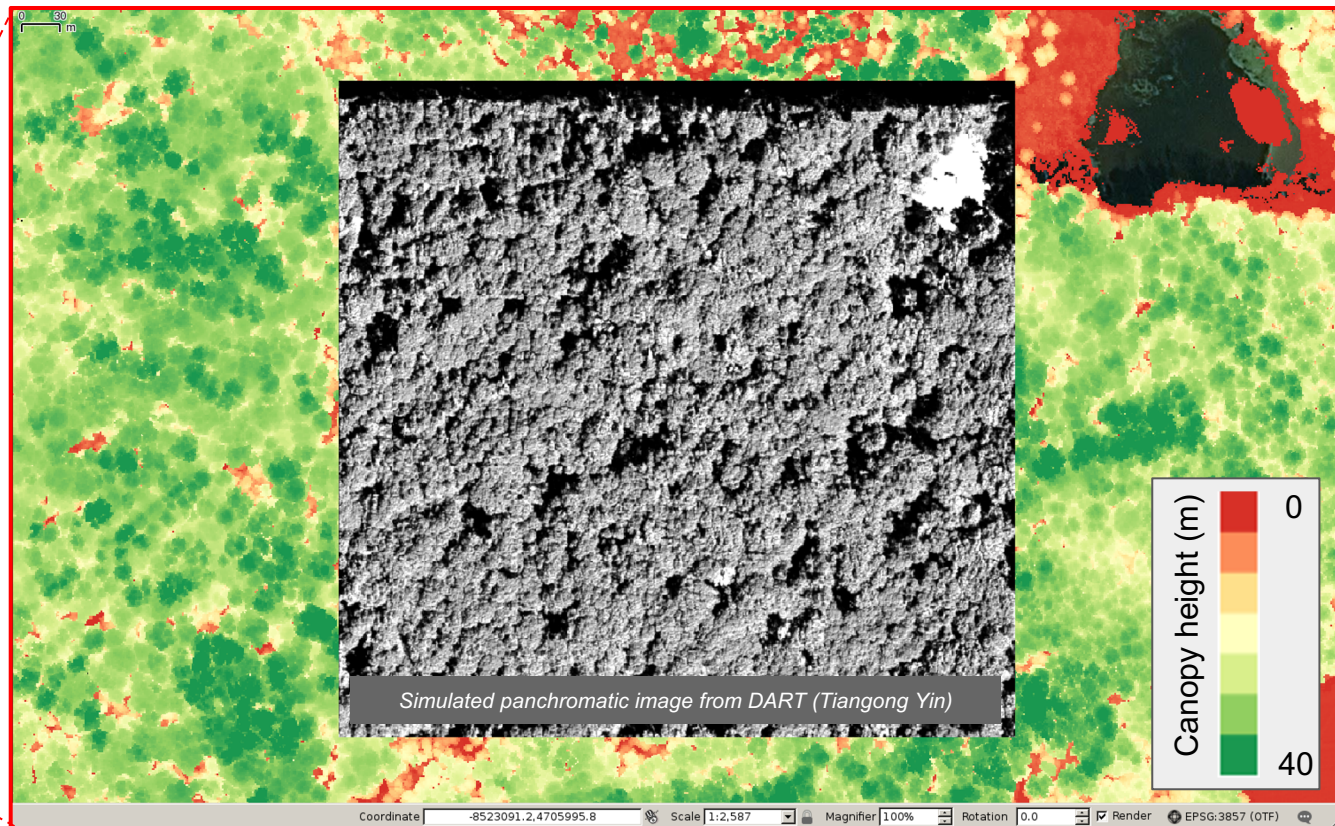
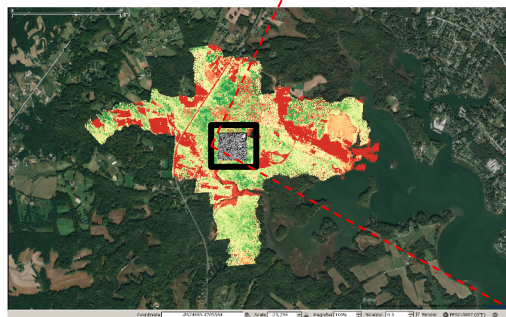


*DART initialized with GLiHT*

# Panchromatic image: DART simulation

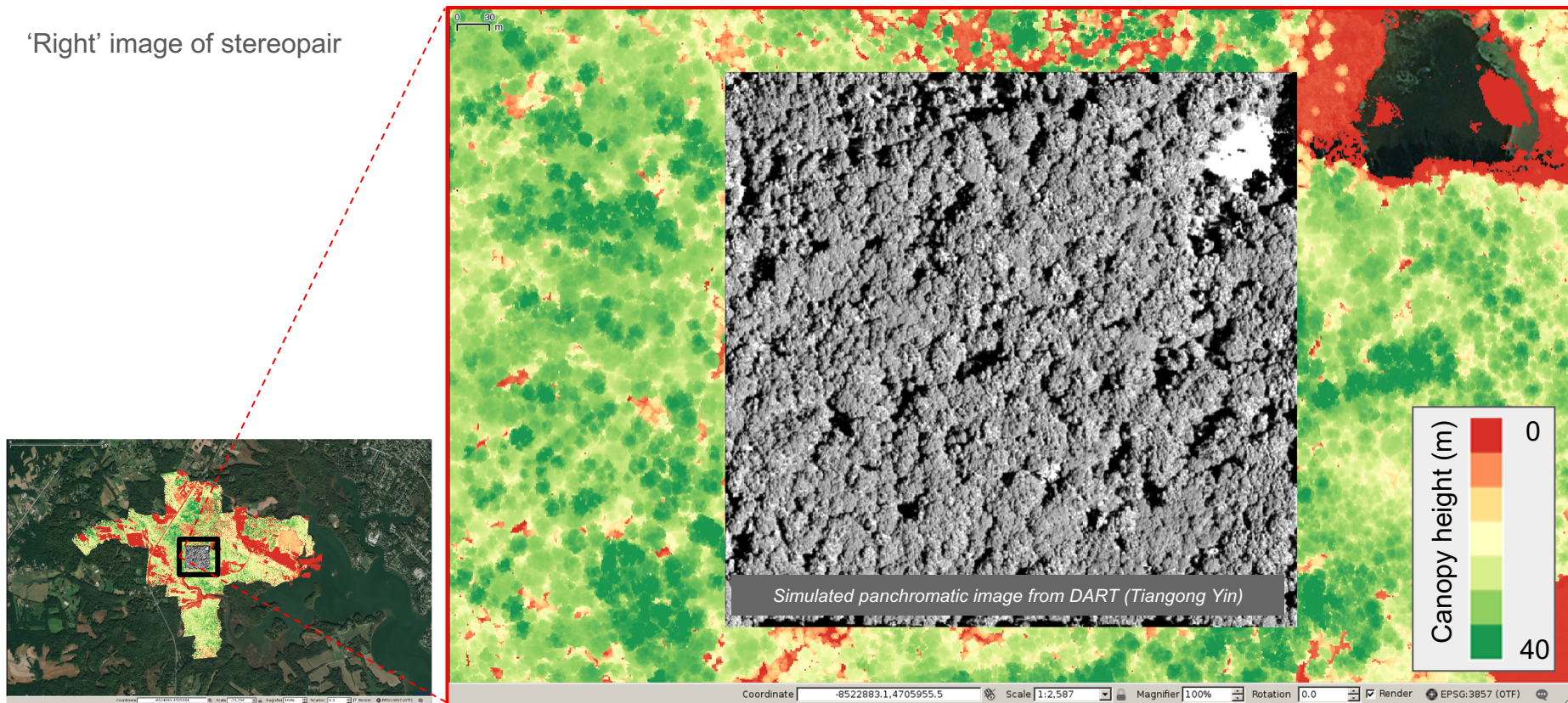
'Left' image of stereopair

~60 cm spatial resolution



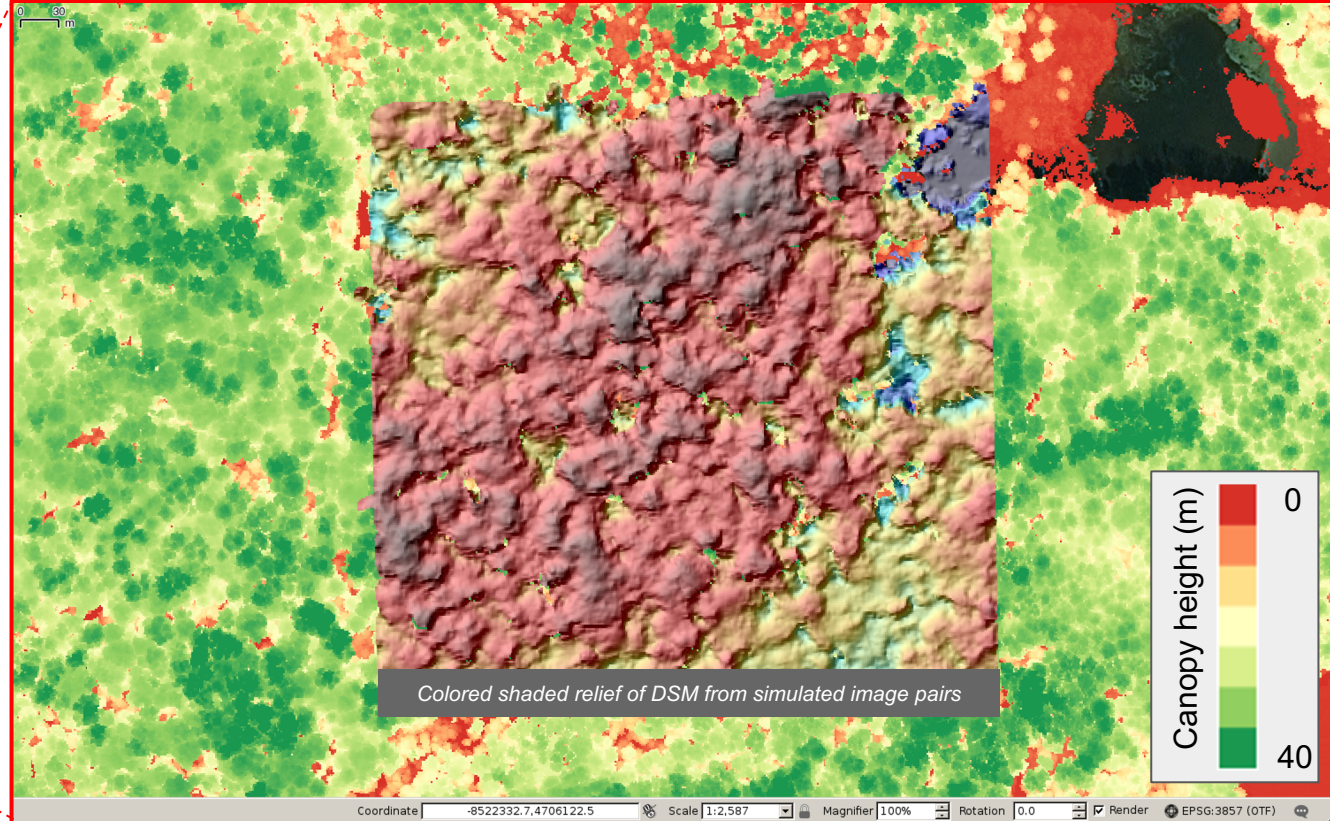
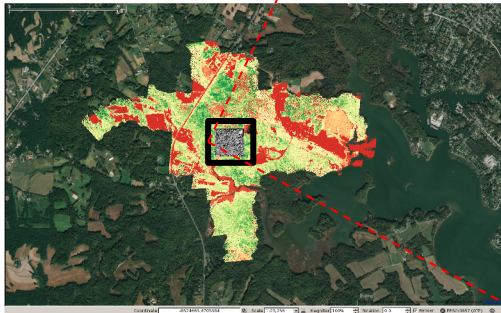
# Panchromatic image: DART simulation

'Right' image of stereopair



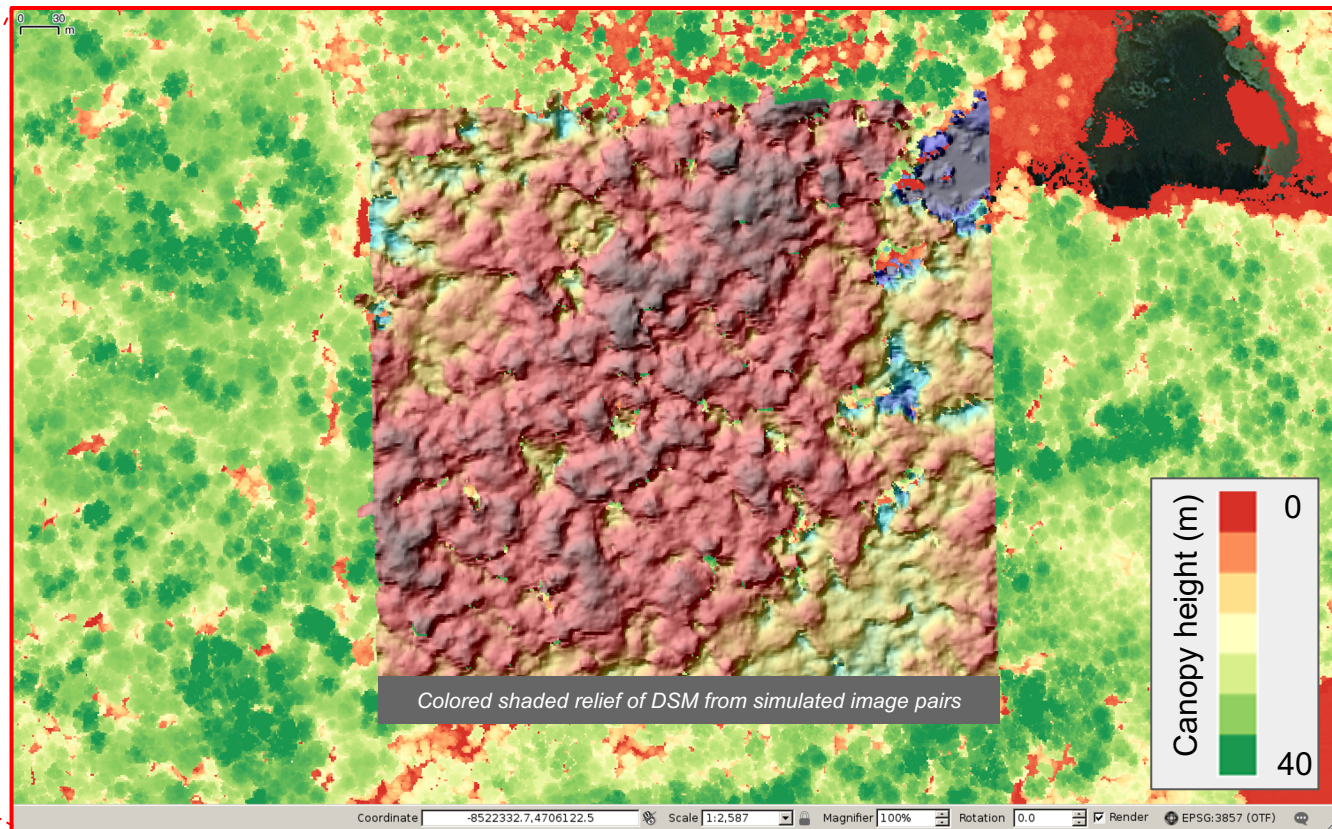
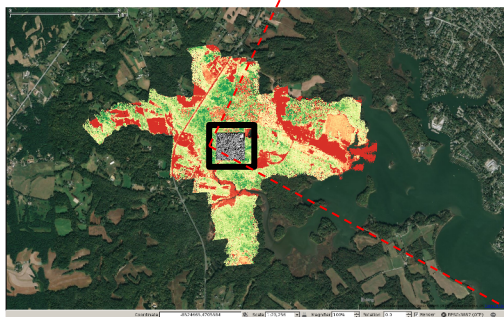
# DSM from DART simulation of stereopairs

- Stereo workflow designed for DigitalGlobe data can apply AMES Stereo Pipeline routines to DART-simulated imagery to return simulated DSMs



# What is the surface elevation error?

- From this acquisition?
  - @ top of canopy
  - @ canopy gaps
- From other acquisitions across the range of sun-sensor-target geometries?
- **Stereo-derived DSMs from DART simulations can provide the full uncertainty profile.**



# Examining other stereo configurations

## ***DART + stereogrammetry + error analysis***

A deep & varied set of simulated stereo data can help build an error matrix to study STV uncertainty from a range of stereo configurations.

- Vegetation conditions: forest type, cover, height
- Stereo geometry: convergence/bisector elev./asymmetry angles
- Local incidence angle
- Seasonality
- etc.

Stereogrammetry workflow:  
[paul.m.montesano@nasa.gov](mailto:paul.m.montesano@nasa.gov)

DART simulations:

Contributors:

[christopher.s.neigh@nasa.gov](mailto:christopher.s.neigh@nasa.gov)

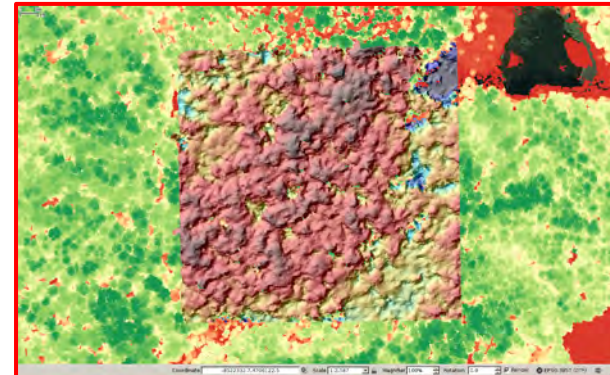
[doug.morton@nasa.gov](mailto:doug.morton@nasa.gov)

**Paul Montesano** |

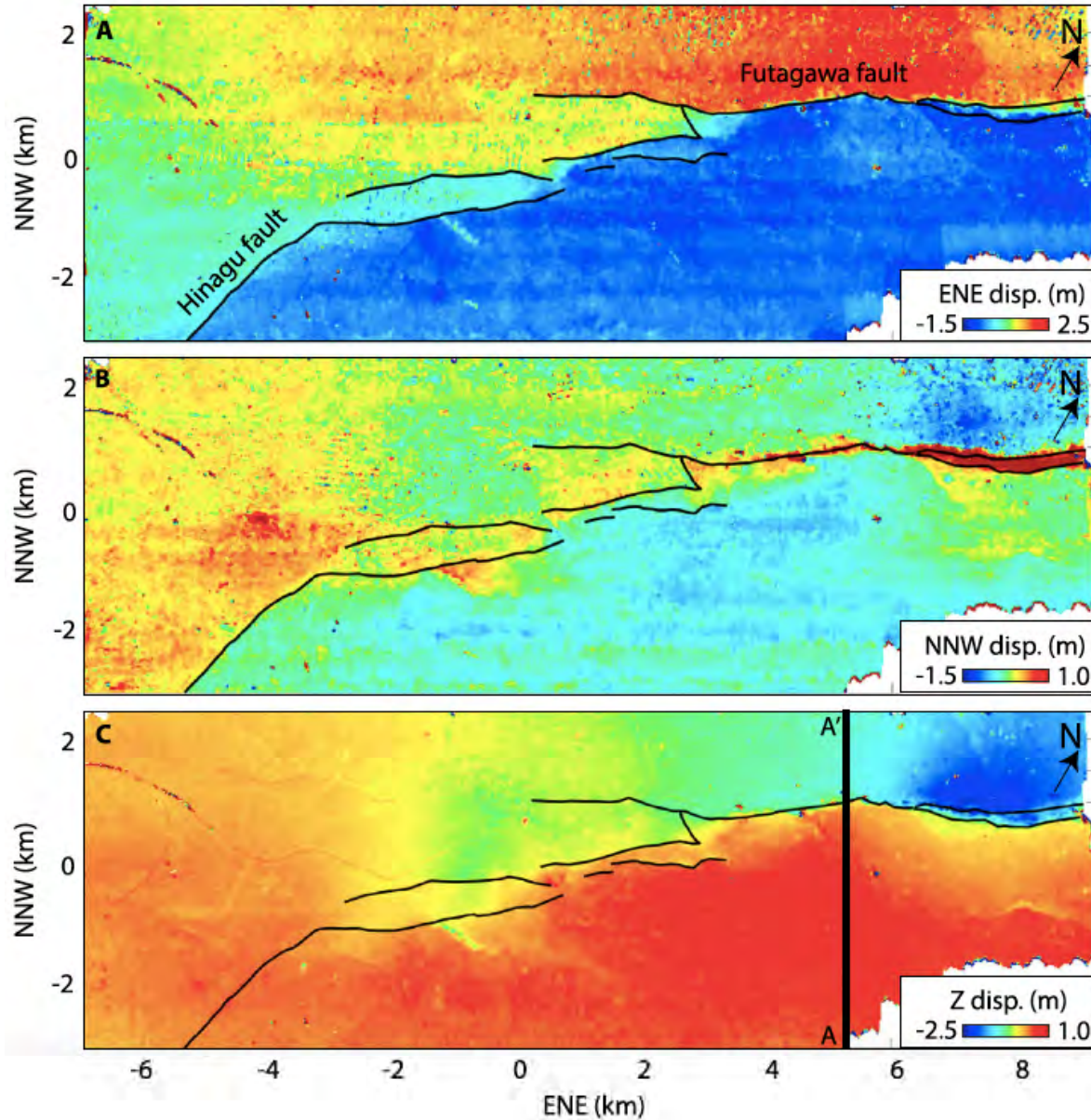
**Tiangang Yin** | [tiangang.yin@nasa.gov](mailto:tiangang.yin@nasa.gov)

Chris Neigh |

Doug Morton |



# Iterative Closest Point Change Detection with Point Clouds



Chelsea Scott

[cpsscott1@asu.edu](mailto:cpsscott1@asu.edu)

Arizona State University



# 4D topography

High resolution topography is a powerful observational tool for studying the Earth's surface.

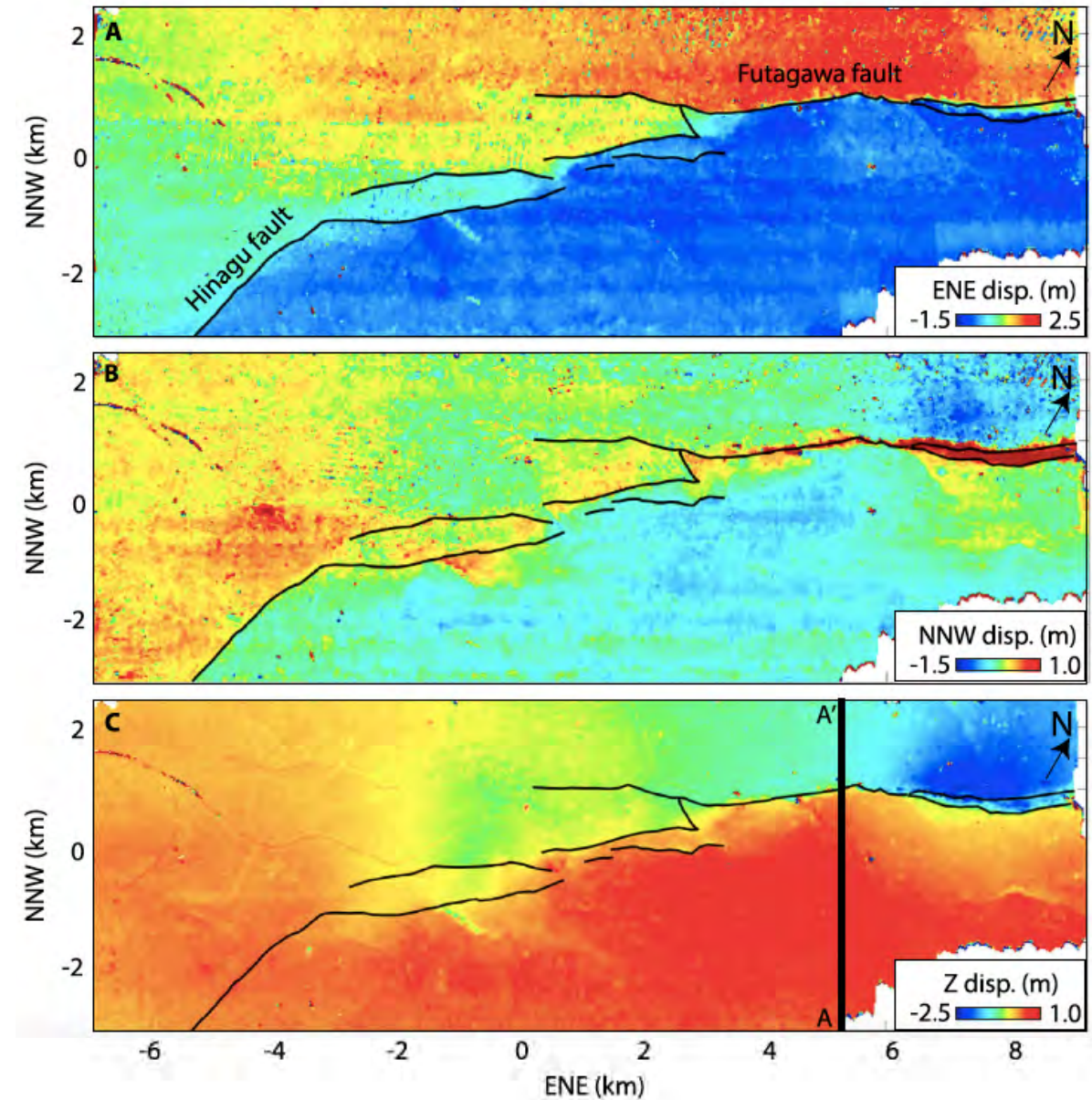
4D topography: Detecting 3D change from growing multitemporal topography datasets

**Today:**

Iterative Closest Point  
Current technology

Challenges and Progress

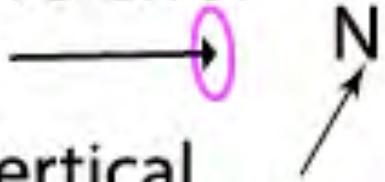
2016 M7 Kumamoto Earthquake: 3D displacement



Scott et al. (2018)

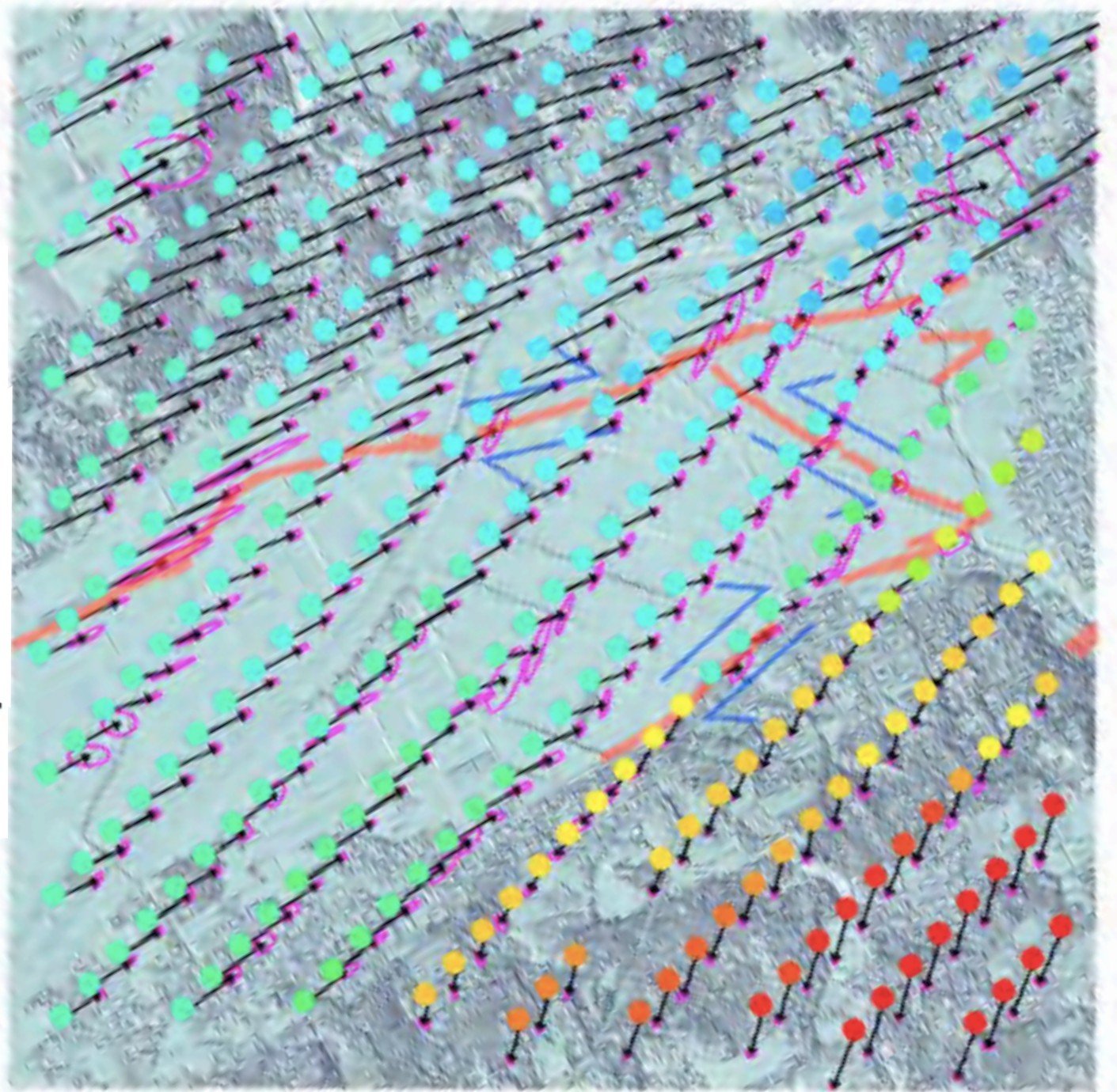
# 3D Topographic differencing

Horizontal  
disp. &  $1\sigma$  error  
1.5 m



Vertical  
displacement (m)  
-1.5 0.75

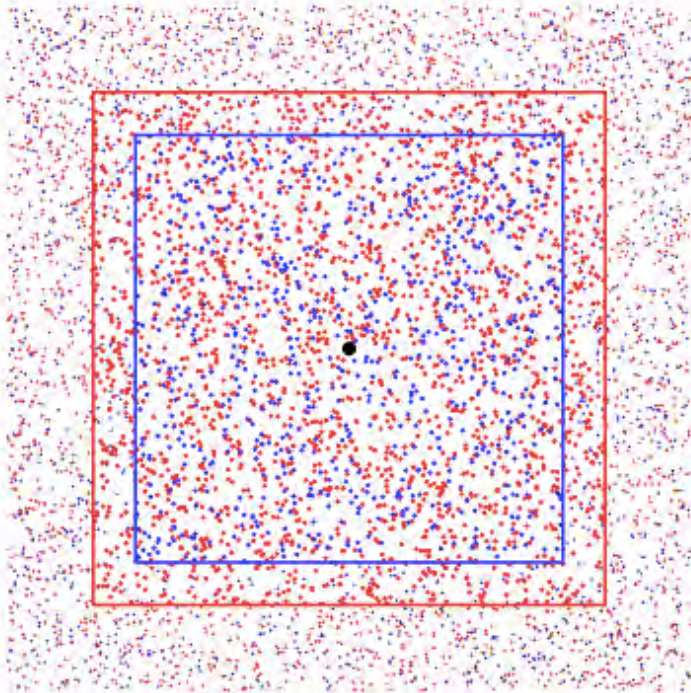
0.5 km



Besl and McKay (1992); Geiger et al.,  
(2012); Nissen et al., (2012; 2014);  
Scott et al., (2018; 2019)

# 3D Topographic differencing

## Iterative Closest Point



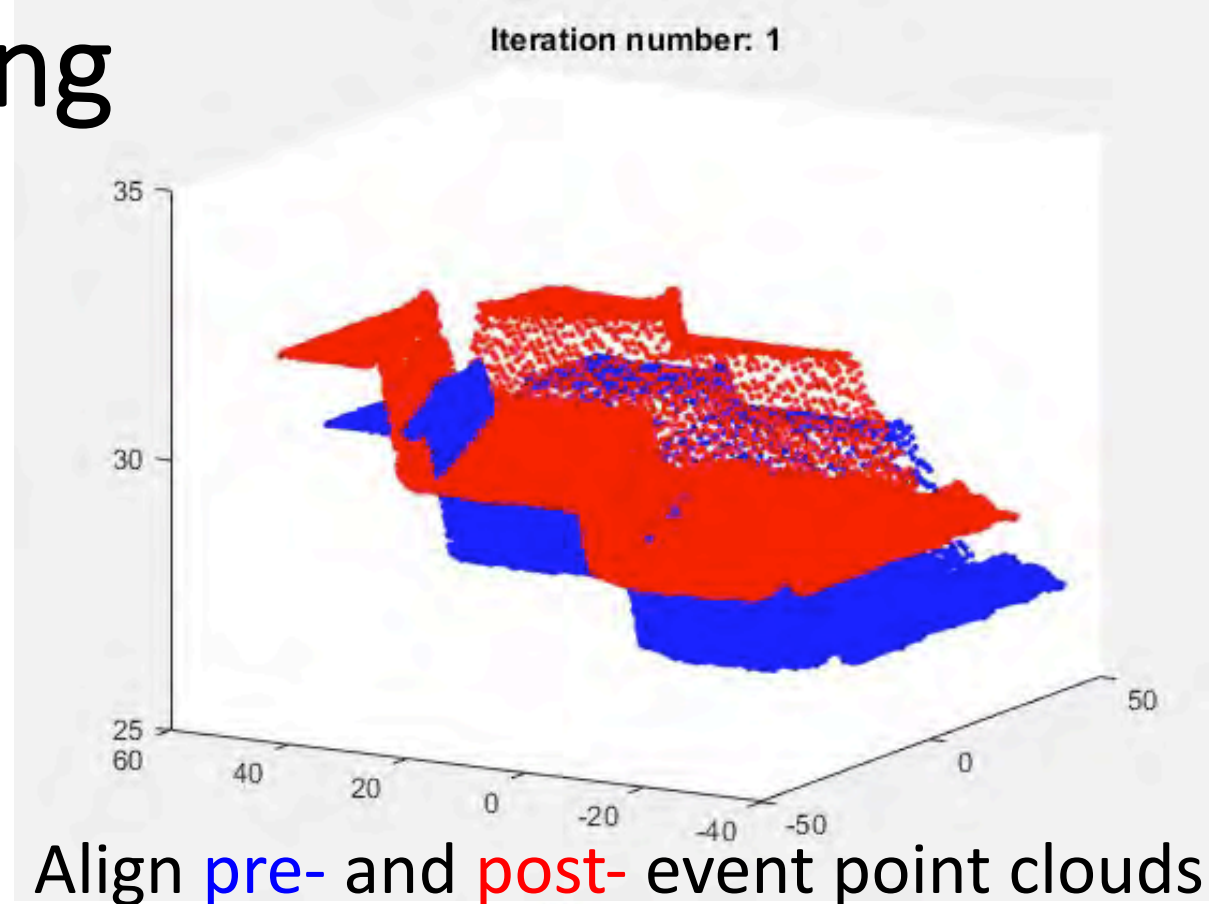
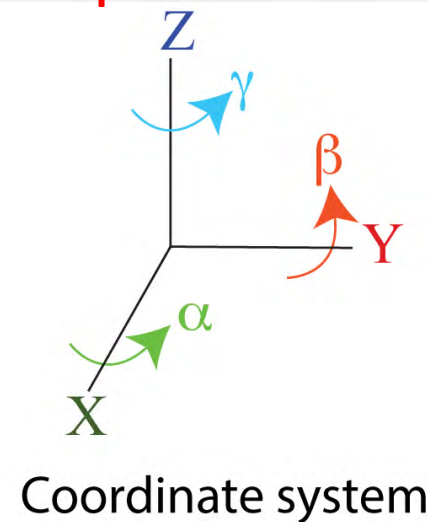
Airborne lidar:  
Several pts/m<sup>2</sup>->  
~50 m ICP  
resolution

● Compare (pre)  
● Reference (post)

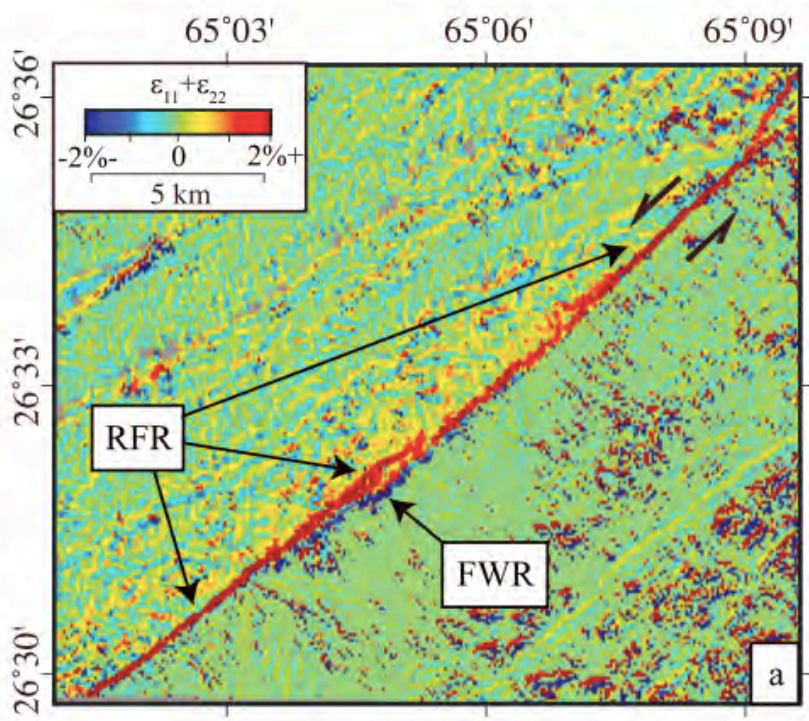
Deformed point cloud =

$$\begin{bmatrix} 1 & -\gamma & \beta \\ \gamma & 1 & -\alpha \\ -\beta & \alpha & 1 \end{bmatrix} \begin{bmatrix} \text{Undeformed point cloud} \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}$$

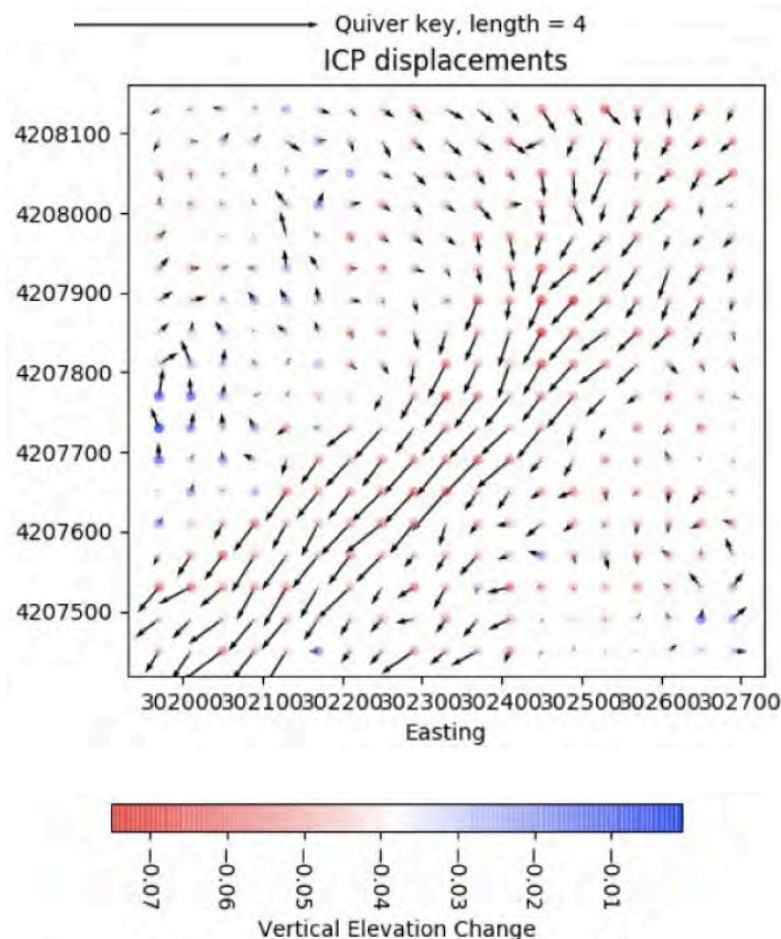
Rotation      Translation



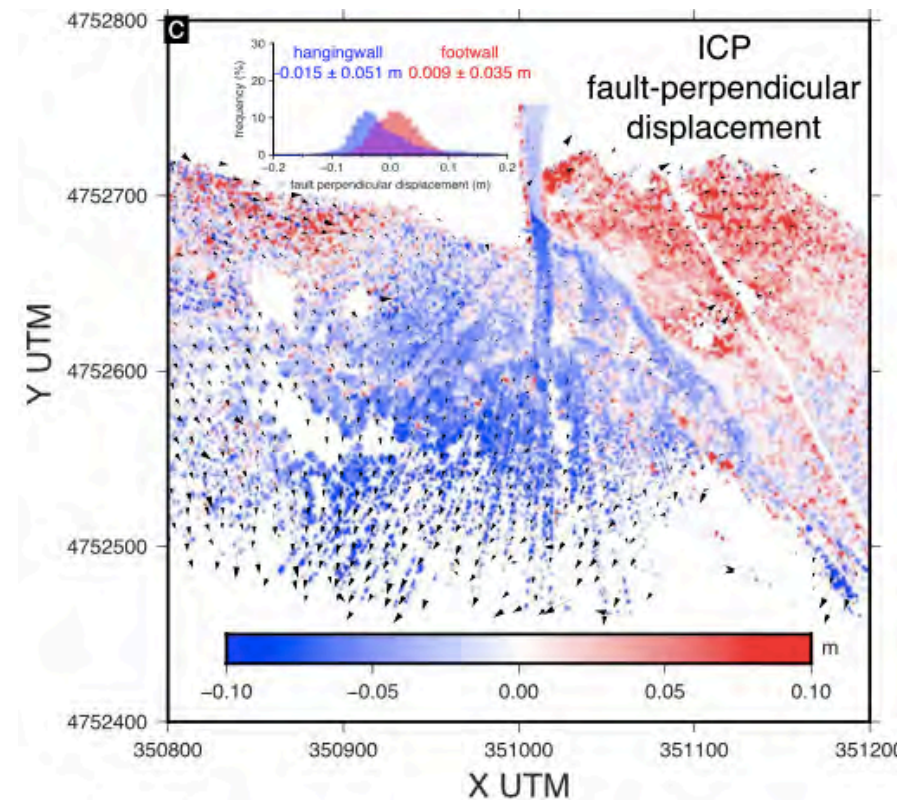
# ICP differencing over multiple scales



**Baluchistan Earthquake, Pakistan**  
**Satellite stereogrammetric DSM**  
**Barnhart et al. 2019**



**Slumgullion Earthquake, CO**  
**Airborne lidar**  
**Processed at OpenTopography**  
**Scott et al. (In Review)**



**Norcia Earthquake, Italy**  
**Terrestrial laser scanning**  
**Wedmore et al. (2019)**

# Current Gaps & Challenges

**Goal:** Efficiently perform differencing from growing topography archive

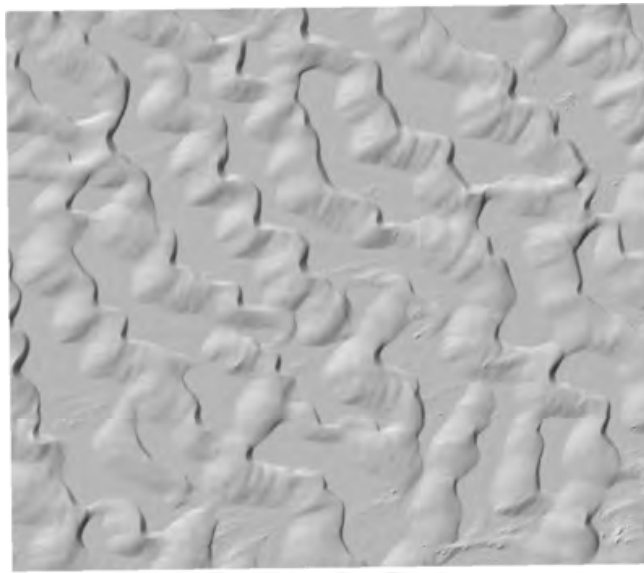
**Challenges:**

Hybrid data

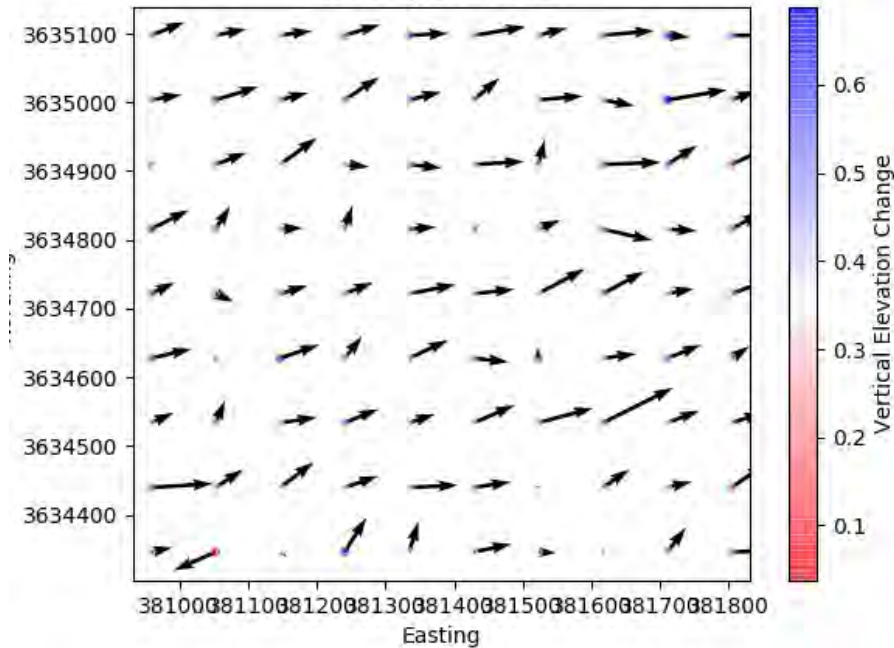
Resolution, noise, vegetation

“Low” surface deformation: M6 EQs, creeping events, postseismic

Efficiently perform differencing



→ Quiver key, length = 4  
ICP displacements



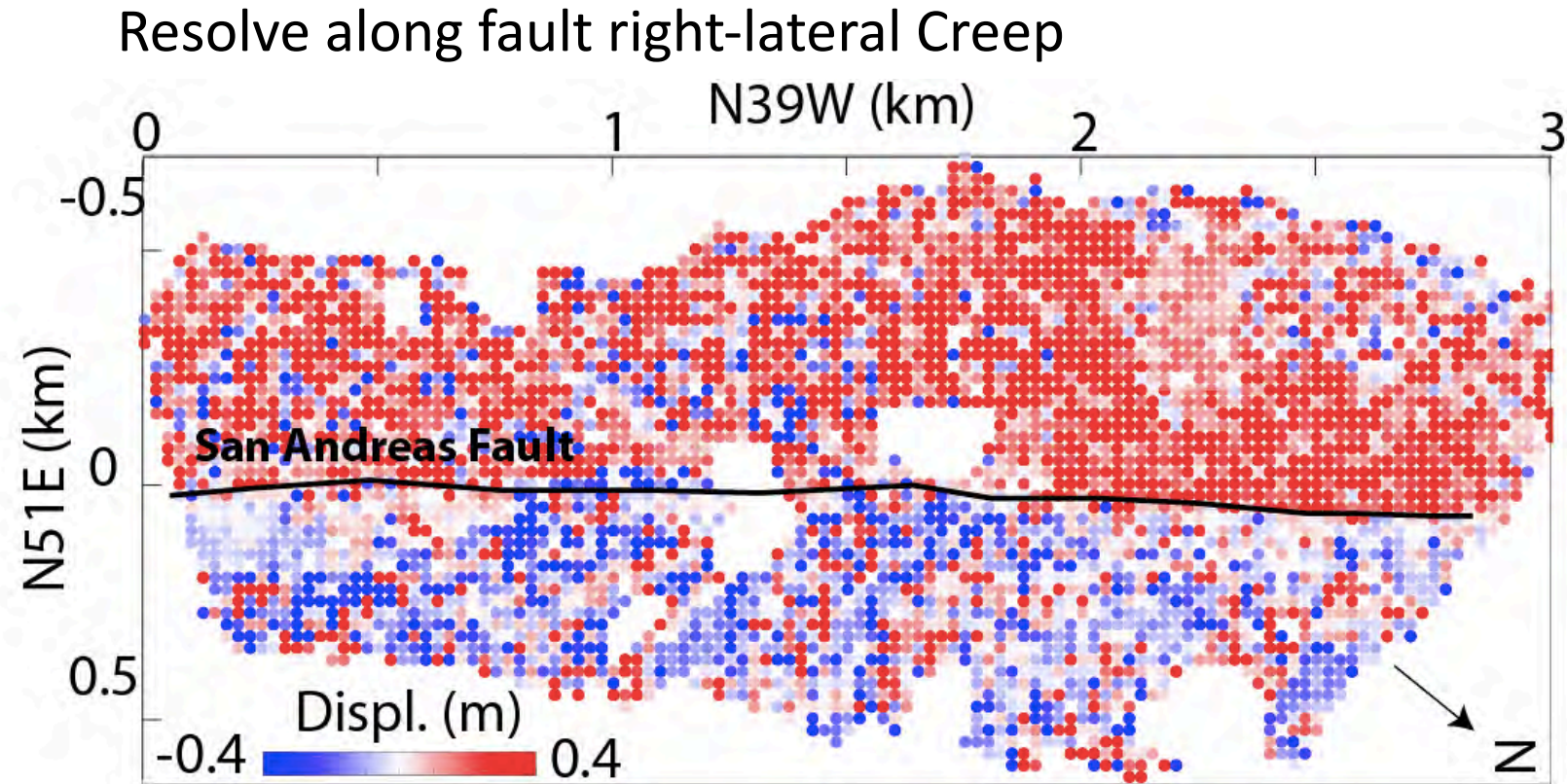
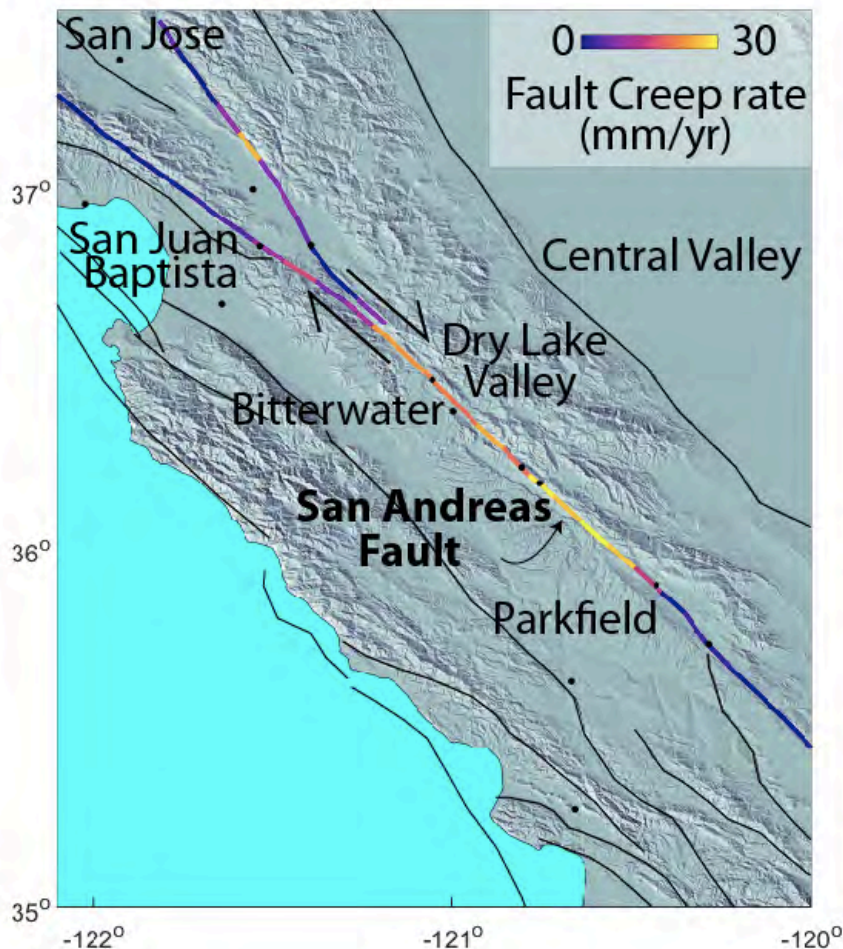
Sand Dune Migration, New Mexico

# Hybrid data and low surface deformation

**Hybrid:** air and spaceborne platforms,  
Lidar and photogrammetry  
Varying resolution, noise sources,  
sensitivity to vegetation

**Low magnitude deformation:**

Typically applied to M7+ earthquakes  
Ideally, M6 EQs, fault creep



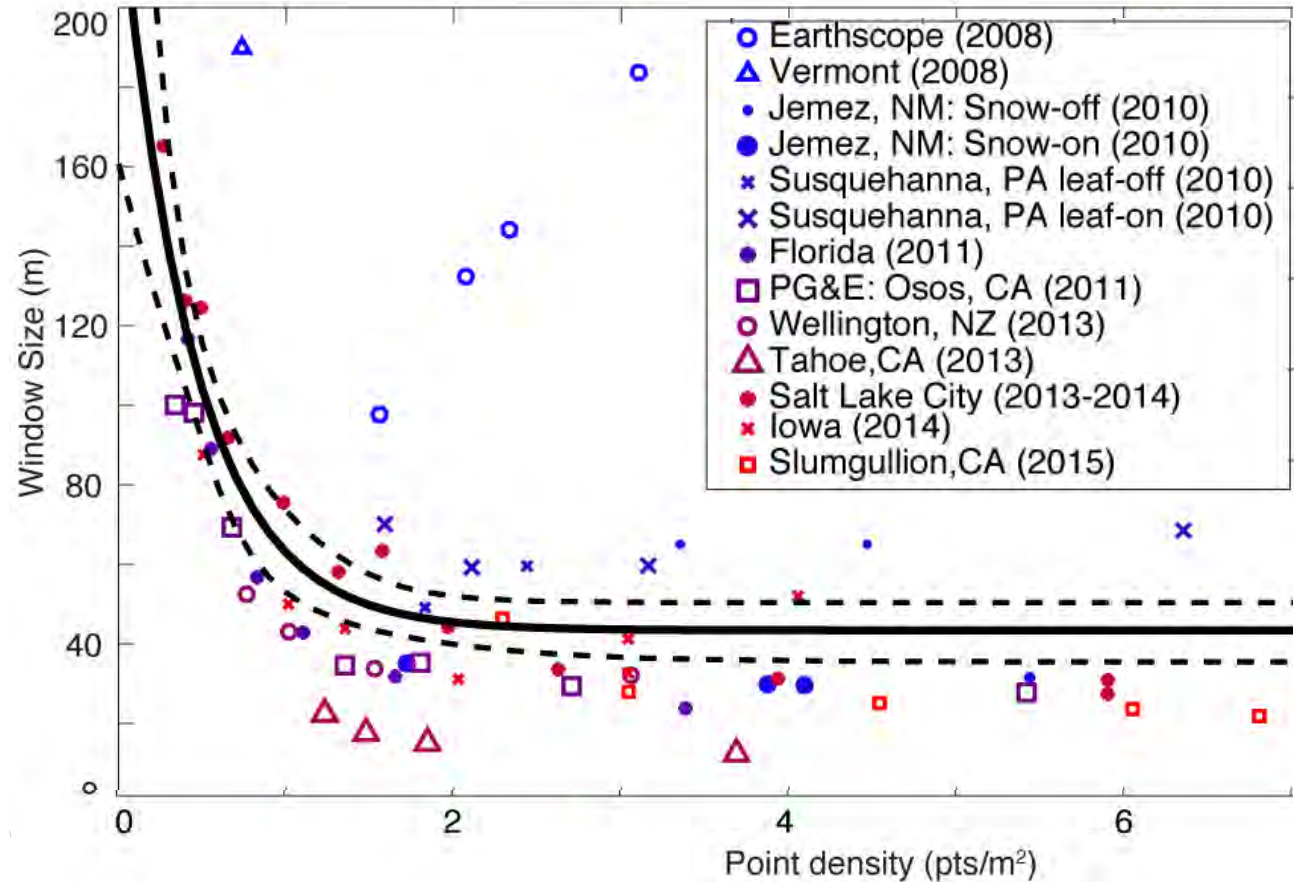
Central San Andreas Fault: 2007 EarthScope lidar & 2017 UAS SfM; 30 cm of creep, Scott et al. (In review)

# Efficiently perform differencing

Develop algorithm and  
cyberinfrastructure to efficiently  
perform differencing

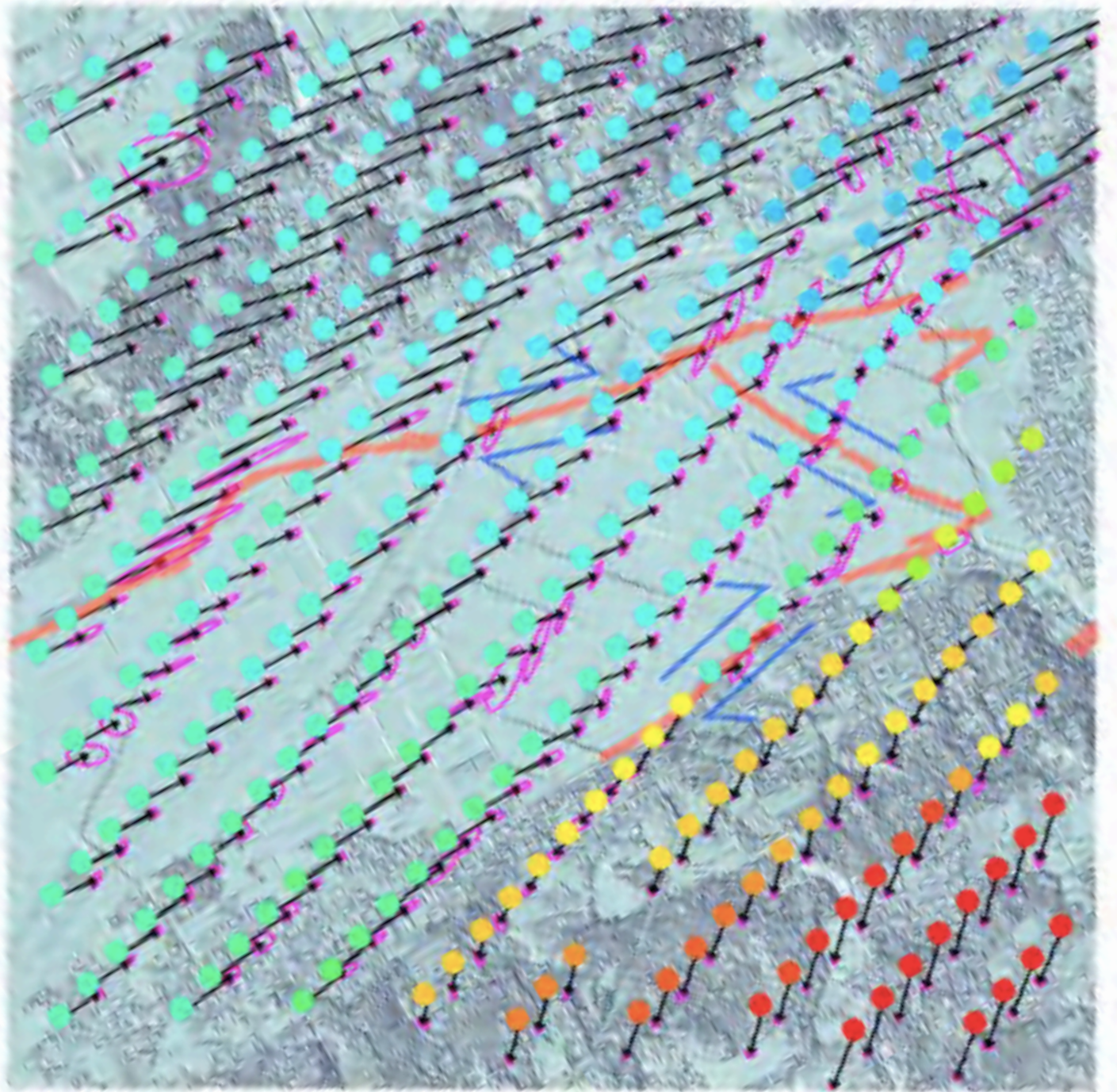
Optimize results for individual  
datasets

On demand 3D differencing implemented at



Optimize ICP resolution given lidar point  
density (Scott et al., In review)

Thank you!



# AI for Surface Topography and Vegetation

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Presentation to the Surface Topography and Vegetation Information Systems Technology Breakout

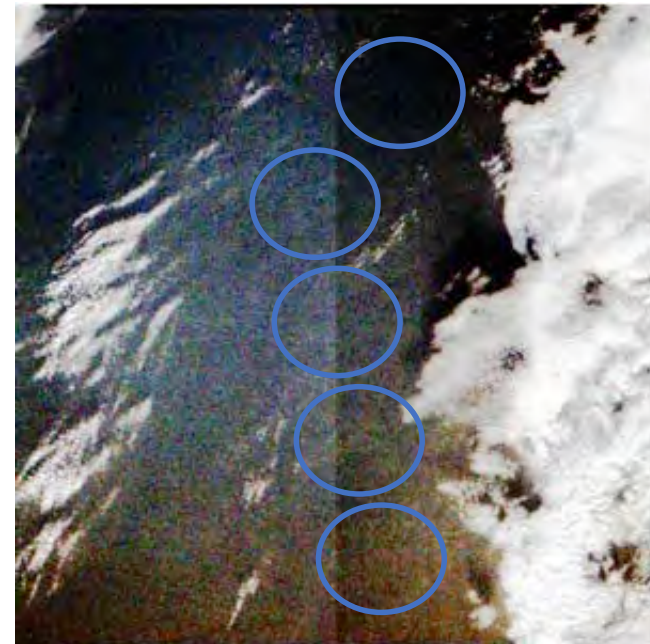
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Government sponsorship acknowledged.  
JP Clearance CL 20-5169.

Predecisional, for planning and discussion only.

# Smart Instruments

## Cloud Avoidance: OCO-3

- Avoid  $\frac{2}{3}$  of Earth covered by clouds.
  - TANSO-FTS is already doing this (Harris for JAXA).
  - Proposed but descope on OCO-3.
  - Est. impact using MODIS statistics\*  
33% → 77% non cloudy
- \* for 40 km out of 700 km wide swath  
avg look 20 degrees off nadir
- All Targetable sensors that want to avoid (or target) clouds should consider.
    - Can adjust classifier to be aggressive or conservative.

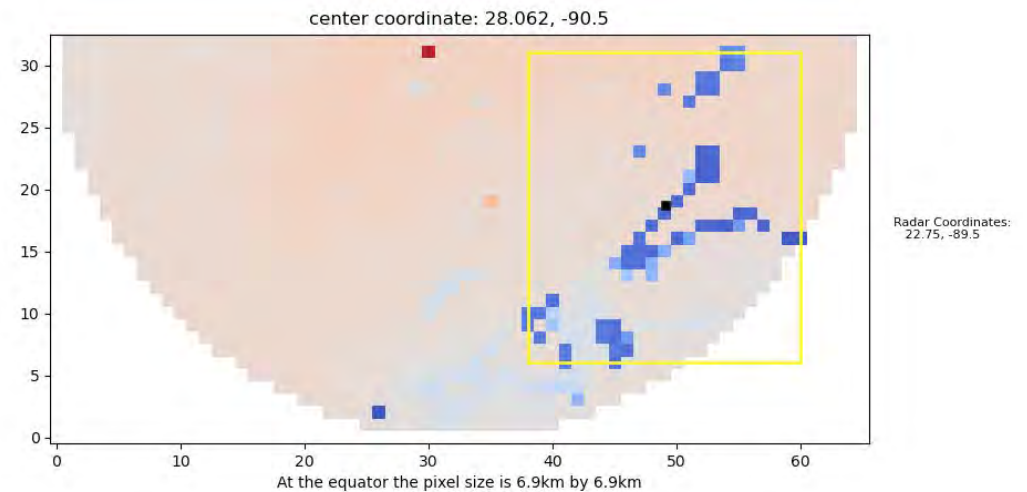


“Take non-cloudy data”

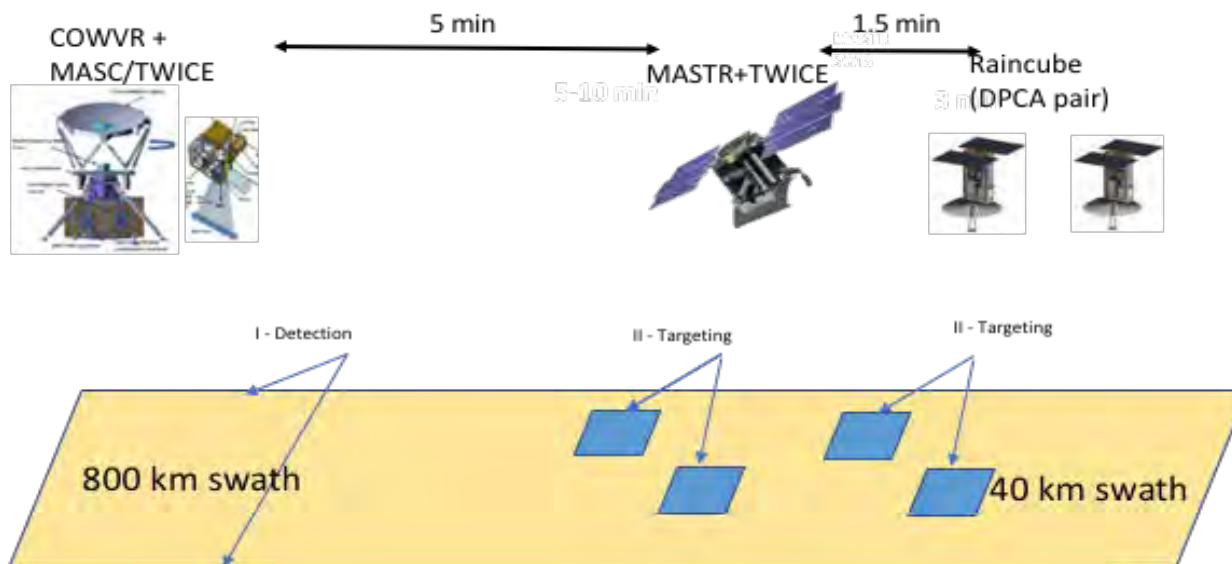
# Smart Ices Hunting (SMICES)

- IIP W. Deal (Northrop) PI
- Uses radiometer to find and target ice storms with radar

“focus on convective core”



# Smart Trains



**Figure 1: Earth Smallsat Train**

*Leaders detect events and re-task followers*

*Coordinated science across s/c with different instruments & capabilities*

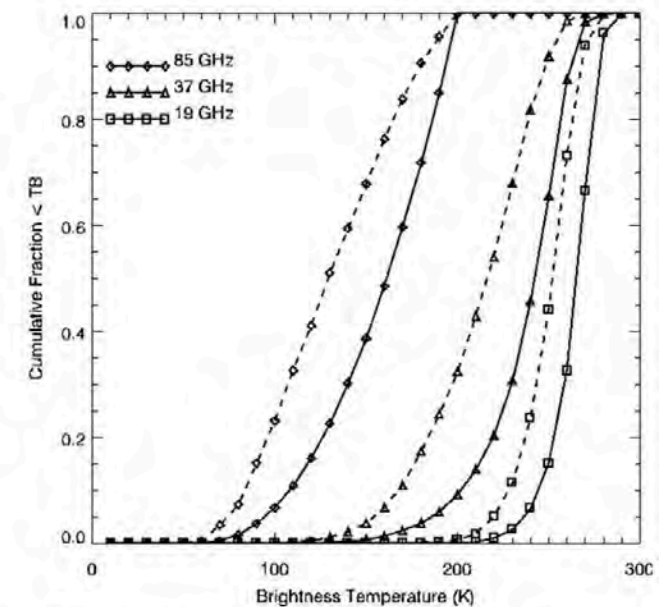


FIG. 1. Cumulative frequency distributions of brightness temperatures for local minima (solid lines) and for hail reports (dashed lines).

Cecil DJ. Passive microwave brightness temperatures as proxies for hailstorms. *Journal of Applied Meteorology and Climatology*. 2009 Jun;48(6):1281-6.

# Sensorwebs - Volcano Sensorweb

- Automated tasking: Volcano Sensorweb
- Links together scores of space, ground, other assets
- Automated Data analysis, triage → prioritized requests
  - ASE/EO-1 service
  - products delivered to stakeholders.
- Over 100,000 alerts/triggers

End Result:

- **Thousands of volcanic scenes 2008-2017,**

*35%+ of said scenes with thermal signatures!*

*Compare to MODIS background < 1% of scenes with active thermal signature.*

*"If MODVOLC detects Thermal, then image with EO-1"*

See Chien et al. 2020 Journal of Aerospace Information Systems

Partners (incomplete list):

MODVOLC

GOESVOLC

AFWA

VAAC

Iceland/MEVO

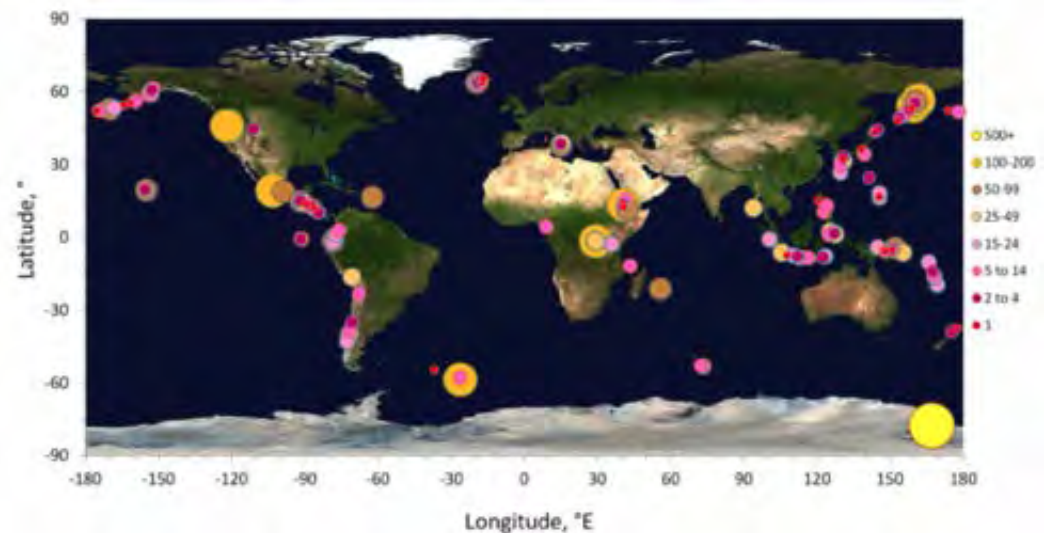
Etna VO (U. Firenze)

MEVO (NM Tech)

HVO (Kilauea)

IEGPN (Ecuador)

CVO (Mount St. Helens)



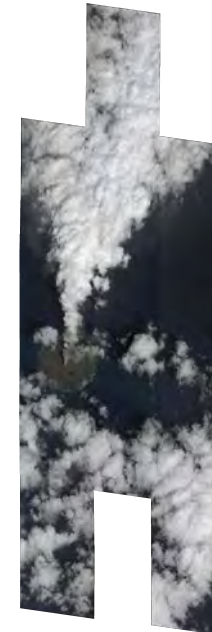
# Current Volcano Sensorweb

- Leverage Commercial assets:
  - Partnership with Planet Labs, discussions with Maxar

Satellite triggers	Trigger Type	Spatial Coverage	Temporal coverage
MODVOLC	Thermal emission	Worldwide	24/7
VIIRS Active Fires	Thermal emission	Worldwide	24/7
In-situ			
Iceland Met Office	Seismic	Iceland	24/7
IGEPN (Ecuador)	Reported	Ecuador	?
Serganomin	Reported	Chile	?
USGS	Seismic	Worldwide	24/7
Other			
Volcanic Ash Advisory (VAAC)	Reported Aviation Ash	Worldwide: 7 regions integrated	24/7



13 Feb 2020  
Bill Mitchell  
(Papua-NG)  
VIIRSvolc



14 Feb 2020  
Nishinoshima  
VIIRSvolc,  
MODVOLC

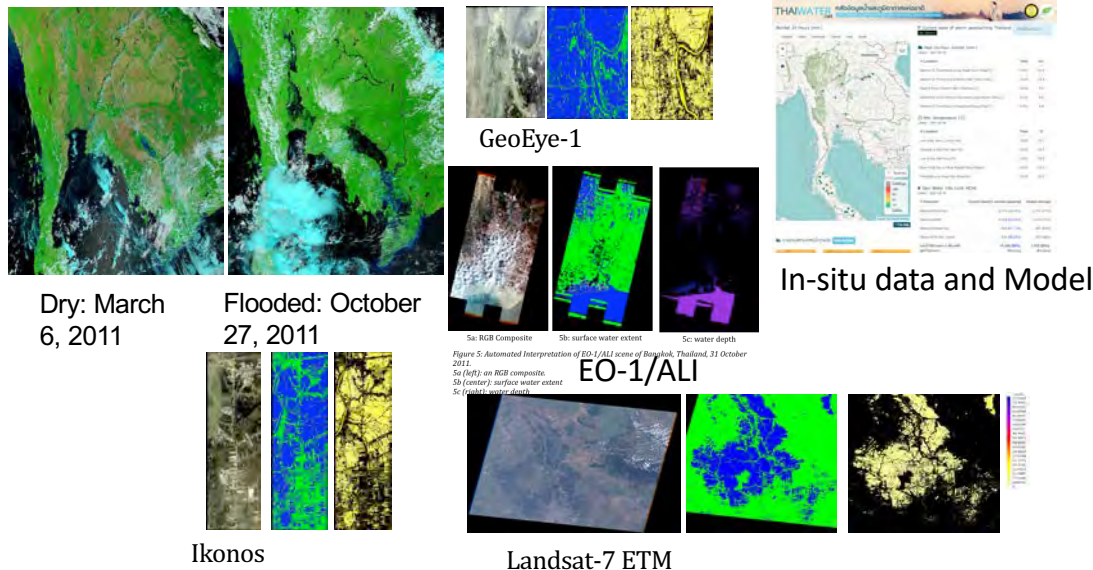


14 Feb 2020  
Mere Lava  
(Vanuatu)  
USGS Seismic

See Chien et al. i-SAIRAS 2020

# Sensorweb: Thailand Flood Sensorweb

- Automated tasking: Thailand Flood Sensorweb
  - Links together space, ground assets
  - Automated Data analysis, triage to generate prioritized requests
    - ASE/EO-1 observation service and others
    - products to stakeholders (water depth map)
  - Fuse data from satellite, ground sensor, and model sources
- +100% temporal hi res coverage for 2010-2011, 2011-2012 Flooding Seasons



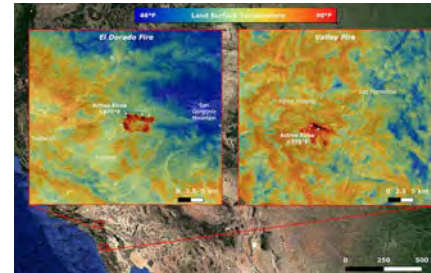
Partners:

- HAI (Thailand)
- Digital Globe (Worldview)
- Geo-Eye
- Radarsat
- Landsat
- LANCE-MODIS

See [Chien et al. 2019, Journal of Aerospace Information Systems]

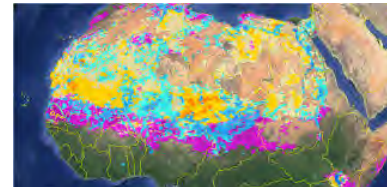
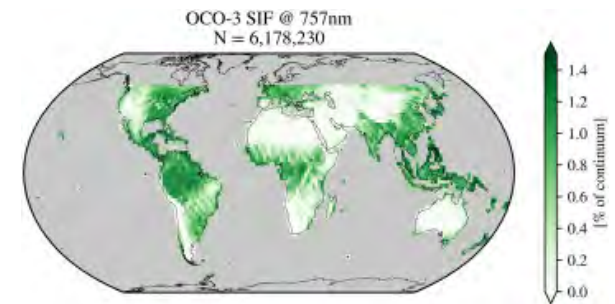
# Mission Design + Operations

- Automated Scheduling Technology used in **Design** and **Operations** for many missions:
  - ECOSTRESS – Design, Operations (POC: S. Hook, K. Cawse-Nelson, D. Freeborn)
  - OCO-3 – Design, Operations (POC: Annmarie Eldering)
  - EMIT – Design, baseline for operations (POC: Rob Green)
  - NISAR - Design, baseline for operations (POC: Paul Rosen)
  - SDC – Design, Analysis (POC: Paul Rosen)
    - Callout (rapid response) assessments for SDC currently being performed using CLASP



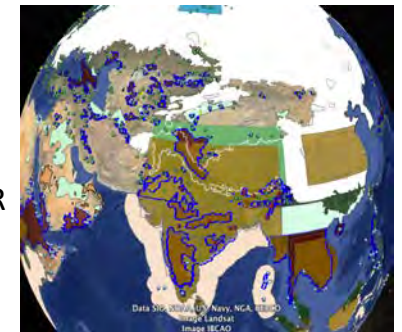
ECOSTRESS CA Fires 09 Sep 2020

OCO-3



EMIT

NISAR



See [ai.jpl.nasa.gov](https://ai.jpl.nasa.gov)